Distance Protection Aspects of Transmission Lines Equipped with Series Compensation Capacitors

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Abstract

In order to meet the high demand for power transmission capacity, some power companies have installed series capacitors on power transmission lines. This allows the impedance of the line to be lowered, thus yielding increased transmission capability. The series capacitor makes sense because it's simple and could be installed for 15 to 30% of the cost of installing a new line, and it can provide the benefits of increased system stability, reduced system losses, and better voltage regulation.[1]

Protective distance relays, which make use of impedance measurements in order to determine the presence and location of faults, are "fooled" by installed series capacitance on the line when the presence or absence of the capacitor in the fault circuit is ***not*** known a priori. This is because the capacitance cancels or compensates some of the inductance of the line and therefore the relay may perceive a fault to be in its first zone when the fault is actually in the second or third zone of protection. Similarly, first zone faults can be perceived to be reverse faults! Clearly this can cause some costly operating errors.

The general approach of interest is a method leading to the determination of the values of series L and C of the line at the time of the fault. This is done by analyzing the synchronous and subsynchronous content of the V and I signals seperately which provides adequate information to compute the series L and C of the line.

Dedication

I would like to dedicate this work to my ***FAMILY*** and friends who have helped me and supported me through the course of my entire education. Special thanks to my immediate family Charles, Valerie, Jason, Paul, Kathy, Gladys, and the late Magdalena Horn, as well as to my closest and dearest friend Kevin.

Acknowledgments

I would like to acknowledge the significant contributions of my committee chair, Dr. Arun G. Phadke. Without his assistance, experience, wisdom, and problem solving abilities, this work, as it is presented, would not have been possible.

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Introduction - The Relaying Problems Associated With Series Capacitor Compensation

As modern transmission systems become more and more heavily loaded, the benefits of series compensation for many of the grid's transmission lines become more obvious. Clearly, adding series compensation is one of the cheapest, simplest ways of increasing transmission line capacity and system stability, lowering losses, and improving voltage regulation.[1] Unfortunately, the series capacitor can undermine the effectiveness of many of the protection schemes used for long distance transmission lines. The introduction of the capacitance in series with the line reactance adds certain complexities to the effective application of impedance based distance relays. The relay will attempt to look at the ratio of voltage to current to determine the distance to the fault in order to decide if the fault is in or out of its zone of protection. It is of course possible to correct the settings of the relay when it is know that the capacitor is always going to be part of the fault circuit. However, that is not always known. By canceling some of the line's series inductance, the series capacitor can make remote forward faults look as if they are in zone one of the relay when the capacitor is switched into the transmission line circuit and the relay setting rules are based on no capacitor in the fault loop (i.e. they can cause the relay to "overreach"). Under these conditions, close-in faults can appear to be reverse faults due to voltage reversal (voltage inversion).[2] More specifically, if we look at a plot of the apparent impedance seen versus the distance from the relay, we see the condition shown in figure I.1. The case depicted in figure I.1 represents a line with 50% compensation. (Line impedance is jX and cap impedance is -j(0.5*X))

It is clear from the plot that when the relay has been set according to a line with no series compensation, it will see many of the faults on the line as reverse faults and will not operate at all. Faults at almost 150% of the line will appear to be zone 1 faults as well. Clearly, some other scheme must be used to protect these lines.

One approach is to slow down the operation of the relay so that the capacitor protection system in use (MOV and/or spark gap and/or circuit breaker) will have time to operate and remove the capacitor (or short circuit its terminals) from service. Then the traditional impedance (mho) relay will function properly.[3] Unfortunately, extending the fault clearing time can lead to instability in the system.

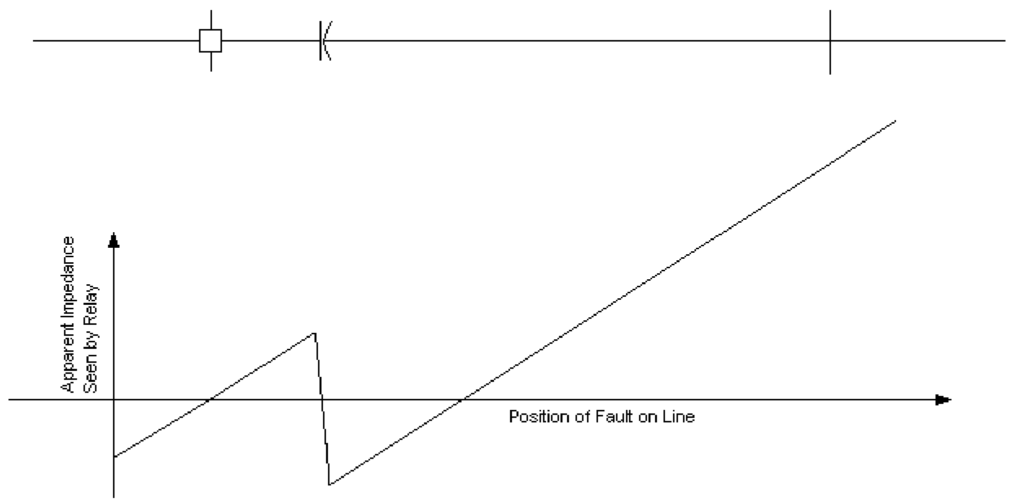


Figure I.1 - Apparent Reactance versus Position on the Line

A viable approach to protection of compensated lines is the use of phase comparison relaying. By comparing the phase angle of the current at one end of that line with the phase angle of the current at the other end of a line, it can be determined if there is a fault in the middle. More specifically if the angles are 180 degrees apart (or close to that), there is a fault in the middle of the line being considered, if not then the fault, is outside of the section of line being considered. The problem with phase comparison relaying is that it requires a communications link between line terminals. Communications links are typically expensive to install and can be a weak link in a protection scheme.

Another problem to note in the protection of series compensated lines is that it can be difficult to accurately measure the 60Hz fundamental frequency component of the voltages and currents. The reason for this problem is simple. When the series capacitor is placed into the system, the system becomes a resonant RLC circuit. When there is some sort of step change in the system (i.e. fault inception), a natural frequency is going to emerge. Since compensation is always going to be 100% or less, the frequency that will be generated is almost always going to be less than 60Hz. The real problem however, is that this subsynchronous frequency is more than likely not going to be an even sub-multiple of 60Hz. When a spectrum is produced using the Fourier Transform, there is a distinct problem caused by frequencies which are close to the fundamental, but not occurring at even sub-intervals detected in a given FFT window. For example, the spectrum of a 45Hz signal mixed with the fundamental (using a 6 cycle data window) will be as in figure I.2:

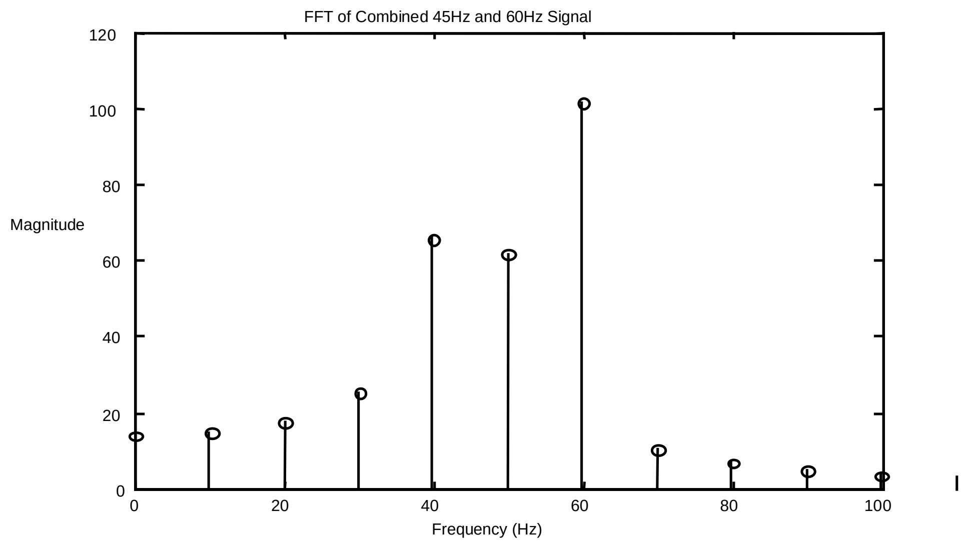


Figure I.2 - Spectrum of a signal containing 60Hz and 45Hz components.

It should be noted that there are a host of other terms that spring up due to the filtering effects of the Fourier Transform. Therefore the component representing the 60Hz magnitude present in the signal has been corrupted by the stray components resulting from the 45Hz portion of the signal. Therefore, in order to achieve accurate measurements of the voltage and/or current phasors, it is necessary to compensate or correct for this corruption. A method will be discussed later which can be used to remove the corruption and determine the correct 60Hz values as well as a method of determining the correct magnitude and frequency of the remaining subsynchronous part of the signal. This is one of the key advancements to be presented for working towards a solution to the series capacitor compensated line protection problem.

There are other obstacles which will plague the solution to the series capacitor compensated line protection problem as well. These include successful computation of the compensated line current for phase to ground faults, and positive determination of whether or not the capacitor was in fact involved in a given fault loop.

Chapter 1 – Overview of Principles of Distance Protection for Transmission Lines

In order to intelligently discuss the problems associated with distance protection for series compensated transmission lines, we must first have a firm understanding of the principles and problems associated with the protection schemes used on non-compensated transmission lines. Once these basic principles are understood, an attempt can be made to expand on them in order to solve the additional relaying problems caused by the introduction of the series compensation capacitors.

1.1 Commonly Used Methods Available for Distance Protection of Transmission Lines

There are three major categories of protection schemes for transmission lines. Two are known as distance protection schemes. These are "Pilot Protection" and "Non-Pilot Protection". The term "pilot" referring to the use of a communications link between the ends of the line to be protected (allowing for instantaneous fault clearing).[2] In pilot schemes, there is the advantage of "knowing" the conditions of the line at *both* ends. The third type of approach are differential in nature. Phase comparison relaying is one of these. This allows for one fairly common solution to the problem of series compensated transmission line protection which is successful in most cases. This solution does not use distance relaying principles, instead it compares the phase of the currents at both ends of the line to see if there is a fault in the middle. This will be discussed more fully later. Aside from phase comparison relaying, there are a number of other pilot type protection schemes to choose from, some of which make use of impedance measurements (distance relaying schemes) and some do not. All of those which take into account impedance measurements must also allow for multiple zone or "stepped" distance protection. The same applies to all distance protection schemes which are non-pilot based.

One of the most critical issues in power system protection of any kind is the speed with which a fault can be cleared. Due to uncertainty in impedance measurements, when protecting a transmission line with non-pilot distance protection schemes (and some types of pilot protection schemes), it is necessary to rely on "stepped" zones of protection. This technique protects any given section of transmission line with multiple zones. Close in faults are cleared instantaneously by zone 1 protection. This protects roughly 85-90% of the line. When a fault is at 95% of the line its location becomes uncertain, based again on accuracy of impedance measurements, whether the fault is actually on that particular section of line or on an adjacent section. Therefore, it makes sense to delay tripping of faults which are perceived by the relay to be between the zone 1 upper limit and the zone 2 upper limit (120-150%) of the length of the line in question. Zone three provides backup for neighboring lines. Delaying a trip on zone 2 and 3 faults allows time for a zone 1 reaction of the relay on the adjacent line if the fault is in fact on that section of line. If it is actually at 95% of the line in question, then it will be cleared in zone 2. This delay insures proper coordination, and helps in the effort to avoid shutting down longer sections of line than are necessary to clear the fault. See figure 1.1.1.

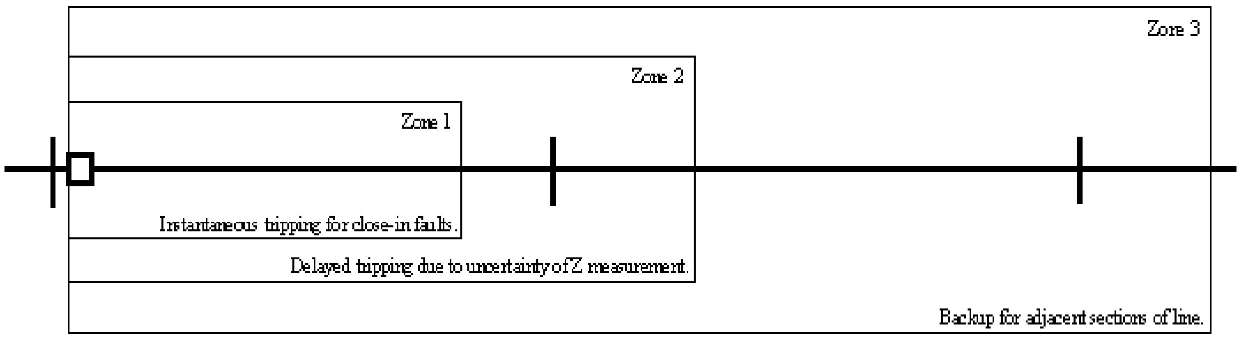


Figure 1.1.1 – Stepped Distance Relaying Zones

Clearly, the problem with all of this lies in faults which are in zone 2. These faults will NEVER be instantaneously cleared from remote ends. Therefore, these faults have the potential to be more damaging to the system as well as system stability immediately following the fault.

The biggest problem with pilot protection schemes unfortunately *is* the pilot (communications link). These communication channels are typically the weakest link in the system and most likely to contribute to the failure of the scheme. Further, they are quite expensive to install and require more maintenance when compared to non-pilot schemes. It is common practice to have a pilot and a non pilot protection scheme for most high voltage transmission lines. Therefore, later on in this document, the concentration will be mainly on the use of non-pilot protection methods for compensated lines.

1.2 Non-Pilot Distance Protection of Transmission Lines

As mentioned before, all non-pilot distance protection schemes are based on impedance measurement (or admittance, reactance etc). Therefore, the non-pilot schemes have some advantages and some disadvantages. The primary advantage to the use of non-pilot protection is that there is no need to construct the communications link (be it PLC, fiber optic, copper, microwave etc.). This is a tremendous cost savings to begin with as none of these methods are cheap. Copper wiring is only good for lines no longer than a couple of miles due to the expense of the high insulation copper cable and the induced current from neighboring power circuits.[2]

In an attempt to better comprehend, visualize, and diagnose the operation of impedance based relays, the R-X diagram is used. This diagram permits the use of only two quantities R and X (or Z and θ in polar form) instead of the confusing combination of E, I, and θ. Further, we are able to represent the relay characteristics as well as the system characteristics on the same diagram and quickly determine at a glance what conditions will lead to relay operation.

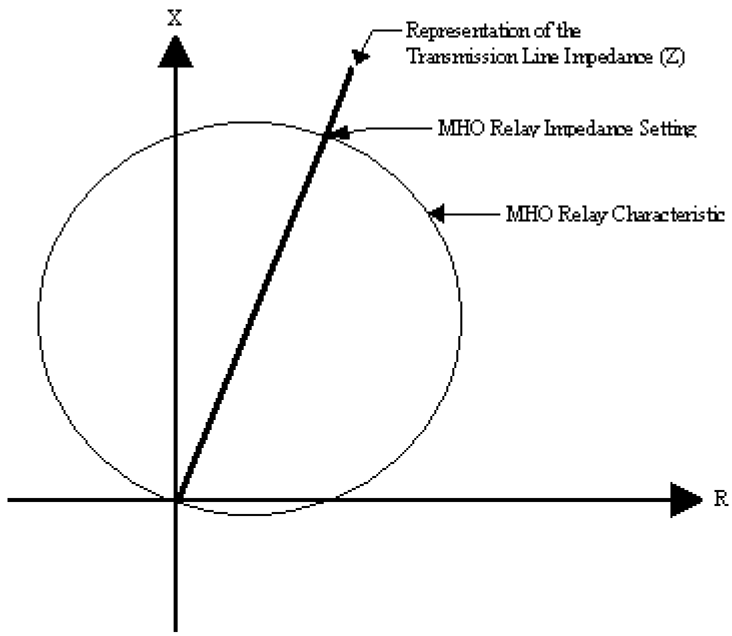


Figure 1.2.1 – Typical Impedance Diagram Showing Line and MHO Relay Characteristic

If we consider a three phase power system, there are a total of 10 different types of faults which are handled by 6 relays for each transmission line. These include 3 phase distance relays, and 3 ground distance relays. With all cases, it should be kept in mind that regardless of the type of fault in question, the voltage and current used to energize the relay are such that the relay will measure the positive sequence impedance from the relay location to the fault.[2]

Once the positive sequence impedance of a fault is known, it should be quite easy to determine the location of the fault and thus make a relaying decision. The only problem which creeps into the computation is fault resistance. In the case of phase to ground faults this is a more serious problem as there is the fault arc resistance in series with tower, footing, and grounding resistances. However, all fault types are subject to the varying arc resistance phenomenon. Therefore, it is of importance to discuss the effect of this resistance on relaying computations and more specifically, the characteristic of the relay itself. As far as the tower footing resistance is concerned (in phase to ground faults), it is roughly a constant between 5 and 50 ohms. This can be compensated for by adding width to the relay trip characteristic on either side of the apparent impedance representing the line. This effectively covers all possible scenarios. As far as fault arc resistance, a generally accepted formula for estimation is:[2]

$$R_{arc} = 76V^2 / S_{SC}$$

In the above equation, V represents the system line to line voltage in kV, and S_{SC} represents the short circuit kVA at the fault location. A worst case can be computed for this value and added to the resistance reach in the relay trip characteristic.

This leads us to the consideration of transmission compensation devices and their effect on relaying. A series capacitor creates a discontinuity in the apparent impedance of the transmission line as viewed from the relay site. This is due to the negative reactance value of the capacitor. Therefore, close in faults appear to be reverse faults as the reactive component of the fault impedance seen is negative. This causes security problems as the relay will be likely to trip for faults which it should not. On the flip side of the coin, under certain conditions, faults near the far end of the line may appear to be outside of zone 1 and may not trip in zone 2 time. This problem causes lack of fast clearing for faults that should cause a trip.

The problems with protecting series capacitor compensated lines are complicated further by the protection schemes used for the capacitor itself. These schemes may incorporate spark gaps (introducing a varying resistance component), Metal Oxide Varistors (introducing a varying and nonlinear resistance), or a circuit breaker which *closes* during faults creating a bypass around the capacitor for high fault currents (thus introducing uncertainty into the calculation).

There are two main solutions in use today to combat the problem. In non-pilot and some types of pilot schemes, there is a time delay which gives the capacitor's protection time to act and effectively remove the capacitor from the circuit altogether. Then, the impedance calculation should be accurate. In pilot schemes such as phase comparison relaying, this is not necessary, however these pilot schemes have drawbacks which will be discussed later.

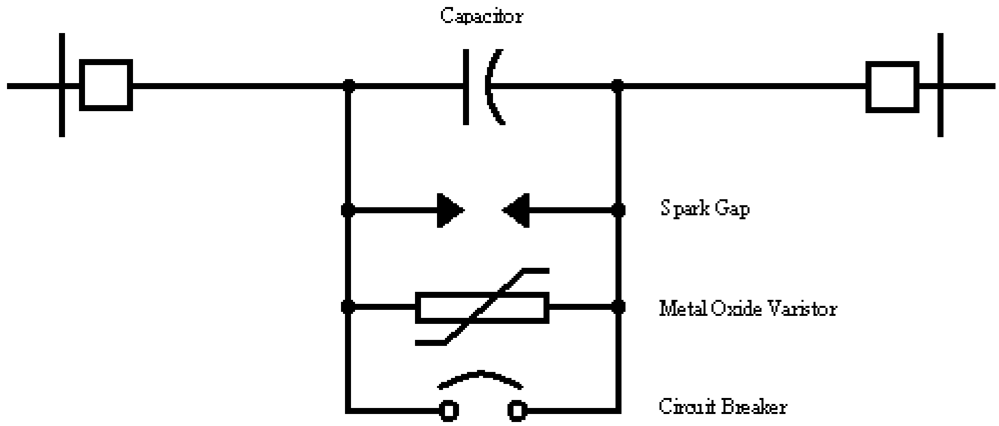


Figure 1.2.2 – Typical Protection Used With a Series Capacitor Installation

There is another important point to consider. As load on a transmission line increases, the impedance seen by the relay decreases. At a certain point, the relay will confuse normal load for a fault. This point, known as the loadability limit of the relay is an important constraint to be considered in the selection of a relay characteristic. Some characteristics will allow for better loadability than others.

1.3 Pilot Distance Protection of Transmission Lines

There are quite a few protection schemes which are based on communication links between the relays at the far ends of a given transmission line. This is in order to realize the benefits of having information from both ends of the line in order to make accurate relaying decisions. Most of these pilot schemes depend on a power line carrier (PLC). This popular method couples a tripping and/or blocking signal in the 10 to 490 kHz range onto the transmission line itself.[2] Other methods for communication include microwave and fiber optic links. These have not been used as often in the past as power line carrier, however these methods are becoming more attractive as the technology becomes less and less expensive.

Pilot protection schemes can be divided into two categories, tripping and blocking. Blocking refers to the fact that the communications signal is used to “block” a trip. When a fault is detected and no blocking signal is present, a trip is issued. When the blocking signal is present, the other end of the transmission line is sending the signal “the fault is outside of our line” and the line does not trip. Conversely, a tripping scheme is one in which the presence of a communications signal indicates that a trip *should* be issued. Tripping is only used when an alternative communications link to the line itself is available. Blocking on the other hand is usually used only for PLC. The reason for this is simple. When a fault occurs on a transmission line which is making use of PLC, the signal between the two ends of the line can become severely attenuated. Under these conditions it is desirable to initiate a trip. Additionally, if a tripping scheme is used, the signal meant to initiate the trip could be lost and the line could fail to trip. Tripping is a viable option chosen when non PLC methods of communications are used such as microwave, fiber optic, or pilot wire.[2] Further, it is better to use tripping methods when possible as they are faster since there is no need for coordination delays.

There are a number of problems that can crop up in a pilot protection scheme that must be considered. While there is the benefit of having information from both ends of the line, there is the potential for that communication to be lost due to the volatility of the communications link itself. When this happens, the scheme can fail in one of two ways. The relays involved can fail to operate (loss of dependability) for an actual fault as they do not see a "trip" signal from the opposite end of the line, or the relays involved can operate when there is no fault (loss of security) as there is no "block" signal seen.

Loss of communications is probably the biggest potential problem with a pilot scheme. Schemes such as directional comparison blocking will still trip for all faults for which they are supposed to, however they may also trip for faults for which they are not supposed to. Any fault picked up by the fault detector will cause a trip in the directional comparison blocking scheme if the communication link fails. This problem can be resolved by using a directional comparison unblocking scheme. This scheme is similar to directional comparison blocking, however in directional comparison *unblocking* there is a signal which is present all the time, (the blocking signal) not just when a fault is detected. This signal is a test to be sure that the communications link is operational. When an internal fault occurs, the carrier shifts frequency to an "unblocking" signal. Then the relay is free to trip. This system is therefore capable of providing a warning immediately when there is a carrier problem instead of waiting for a false operation of the relay to indicate that there is a problem as would occur in the directional comparison blocking scheme.

Speed is always considered to be of paramount importance in protective relaying, particularly on EHV power lines where damage to equipment and deterioration of system stability occur very quickly when a fault is not cleared. The problem with using a blocking scheme is that there must be a coordination delay in order to allow time for the blocking signal from the opposite end of the line to start. Therefore it becomes desirable to implement a tripping scheme if a communications link other than the line itself is available.

Another serious problem which can crop up when using PLC is a false trip due to electrical noise which can be caused by switching in the substation, or transients due to other relay operations. These electrical phenomena can cause the PLC signals to be misinterpreted. To solve this problem, of course one would like to engineer in as much shielding and stabilization for the circuitry as possible and economical, however there are other tripping pilot schemes which help to make the system more secure. One such scheme is Permissive Overreaching Transfer Trip in which an overreaching fault detector is used. This scheme uses the directional overreaching relay as both a fault detector and a permissive interlock to prevent noise initiated trips.[2]

There is another option in the family of pilot relaying schemes left to discuss. This method is Phase Comparison Relaying. This method does not make use of impedance relays as other methods do. Rather, the relative phase angle between the currents at the far ends of the line are compared. When these currents are in phase, it is obvious that the current is entering one end of the line and departing from the other and that there must not be a fault. When the currents are 180 degrees out of phase, there is clearly current entering the line from both sides and there is then clearly a fault on the line somewhere. Phase Comparison Relaying is of particular interest to this investigation as it will work properly for lines which are protected with series capacitors. It is the only scheme which will work accurately without modifications or the addition of time delays. Further, there is no need for PT's when using phase comparison relaying as the only concern is with the phase of the current. There is still however one drawback which is that this scheme is still a pilot scheme and therefore requires a communications link between the far ends of the line. The other down side is that this scheme does not provide back up protection for the line, or for the neighboring sections. In order to have some redundancy or a backup, another relay must be used.

1.4 Limits to Fault Location Accuracy

In system protection and maintenance, one of the most crucial issues when dealing with transmission lines is determining the location of a fault. From a relaying perspective, it is important to get a very close estimate very quickly in order to trip only the appropriate segments of a line. When investigating a fault for the purposes of maintenance and repair of the line itself, it is necessary to compute an extremely good estimate of a particular fault location. If there is an error of 5% in the estimate of fault location on a 100 mile line, that means a potential error of 5 miles. When a crew must go into the field and visually inspect to find the location of the fault for repair or maintenance purposes, that is a lot of line to survey. Therefore, it becomes important to compute the best possible estimate to cut maintenance and repair costs as well as to provide effective, efficient, reliable protection.

There are a number of sources of error which can be introduced into the computation of a given fault location. These include transducer error, model error, measurement error, and algorithm error. The different types of errors have different levels of impact on the final outcome depending on what sort of protection or analysis is being performed. For instance, clearly algorithm error only applies to microprocessor based relays and fault recorders, whereas transducer error will affect even the most traditional electromechanical distance relay.

Transducer errors are those errors introduced in voltages and currents by the instrument transformers. While refined manufacturing techniques can dramatically reduce the error introduced by transducers, there will always be some variations in materials and construction of the units thus making it impossible to completely eliminate error. Further, climatic changes as well as system condition changes can have an impact on these current and voltage transformations. CCVT's are sensitive to temperature changes, age, and varying burdens. CT's have an inherent weakness, saturation. Saturation occurs when primary overcurrents cause the flux in the CT core to become excessive and the CT then moves into an operational state of extreme inaccuracy.[8]

Clearly, transducer errors will affect all forms of protection and analysis from the most primitive electromechanical impedance relay to the most complicated microprocessor based fault locator. The fact that the transducers act as the eyes of any system which enable it to "see" the power line (or equipment being protected) means that the unavoidable error in the transducers is the minimum error which can be seen in a fault location determination. While it could be possible to correct for these errors, the correction factors would be different for every transducer. Further, these factors would have to be adjusted throughout the life of the unit as it ages, as well as with any significant climatic or system changes in order to keep them accurate. This would make the process of correcting for transducer errors very costly and highly impractical.

Next we should consider measurement errors. These errors come into play in one form or another in electromechanical, electronic, and digital systems. They are caused by phenomena ranging from simple signal attenuation, to A/D conversion errors, to dc offsets, to nonlinearities in the interface circuitry. Nonlinearities and high harmonic content will tend to affect electromechanical devices more since these factors cannot be compensated for in basic electromechanical devices as they can be in the algorithms and circuitry of digital and/or electronic devices. Typically these measurement errors are small when a given system has been well designed and appropriate hardware and algorithms are in place. Usually measurement error is considered to be negligible in contrast to other sources of error. [4]

Model error is another source of poor fault location accuracy. Failure to take into account such things as shunt capacitance, line transposition (or lack thereof), shunt reactors, and ambient temperature (causing line sag) could result in “model” errors. These errors can affect all protective devices. Poor initial design and relay settings due to inaccurate line models will plague an installation during its entire service life.

The final major category from which error emerges in fault location determination is the algorithm. Of course it is clear that only digital relays would suffer from this particular problem. Algorithm error mainly refers to error caused due to an inappropriate choice of numerical techniques which could be used to solve the problem. There are many approaches that will give ballpark solutions, however there are only a few techniques which will give accurate solutions. The majority of the high accuracy algorithms are based, in some form or another, on the Takagi algorithm which has been thoroughly used and tested and can be found in many modern commercial products.[4] A chosen algorithm should also be robust so that it is not significantly affected by missing data, slight variations in line parameters, or other slight variances.

With a good understanding of distance relaying and its most troubling problems (as well as some methods of solving these problems) it is time to turn to the specific problem at hand: “How to improve single ended methods used for protection of series compensated transmission lines?”

Chapter 2 – Single Phase Consideration of Series Compensation Issues

Here a single phase model will be considered for the purposes of explanation of the theory and technique that could potentially be used to solve the problem in a single phase model without MOV operation. (i.e. before the MOV or other protective elements operate)

2.1 Simple Series Representation of the Fault Circuit

The final result we seek is to know the actual values of series capacitance and series inductance of the line in question if at all possible (and if not, to know if the capacitor was part of the fault loop). Considering two frequencies at which voltage and current measurements are made, there are subsequently two available impedances, one for each frequency.[5] This leaves two equations and two unknowns, and as a result, there should be a unique solution to the problem. The model of the line which must be used to solve the problem will neglect series resistance. This is an acceptable assumption since it is possible to separate the real and imaginary parts of the impedances calculated at each frequency and solve using only the imaginary part. One must however ignore the shunt capacitance values, which will likely cause some error. This error is slight and not significant since we only need to have an estimate of the series C value of the line in order to infer the exact value based on the known value(s) of installed C. If the installation has a variable capacitor, then our results should still be accurate enough to make a determination of fault location which is adequate for relaying decisions.

Given this, the resulting single phase model is very simple. It consists only of a series inductor and capacitor which symbolize the lumped impedance and sum of all series capacitance included in the fault loop. A diagram is shown in figure 2.1.1.

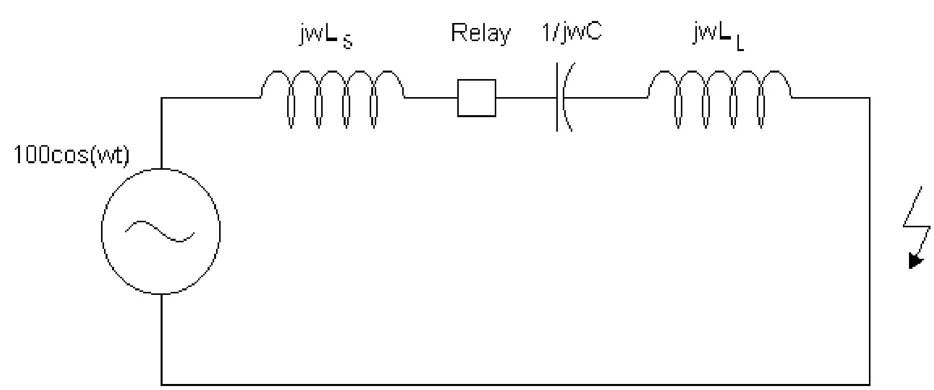


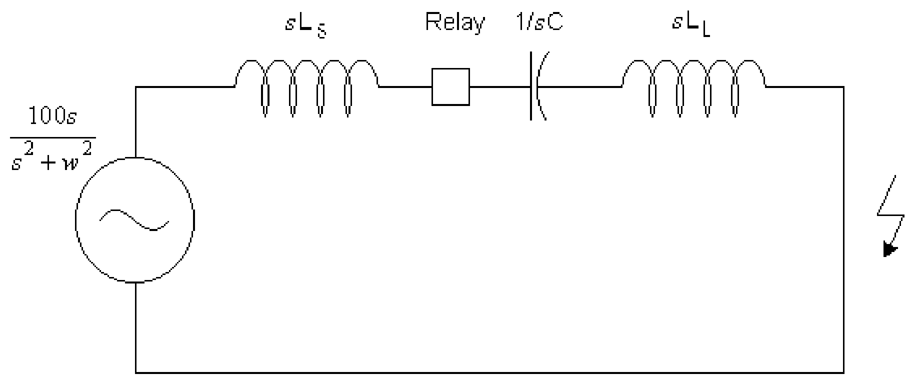
Figure 2.1.1 - Single phase model of faulted circuit

Next it would be logical to explore the theory behind the assumption of subsynchronous frequencies in all faults involving a series capacitor.

2.2 Examination of Presence of Subsynchronous Harmonics in Resulting Waveforms

If we consider the frequency domain representation of our circuit it would appear as shown here with the previous diagram's inductor's value replaced by "sL" and the capacitor's value replaced by "1/sC".

Figure 2.2.1 - Laplace Domain representation of the single phase test circuit.



The fictional relay in the circuit is located at the position marked with a box, therefore the voltage and current seen at this location will be expressed as (Laplace domain):

$$V_{relay} = \frac{(V_{source})(sL_L + 1/sC)}{(sL_L + sL_S + 1/sC)} \qquad (1)$$

$$I_{relay} = \frac{V_{source}}{(sL_L + sL_S + 1/sC)} \qquad (2)$$

Assuming a perfect sinusoidal source of 1 volt, $V_{source} = s/(s^2+\omega^2)$. Substituting this into equations (1) and (2) above, and performing an inverse Laplace transform on the result yields equations (3) and (4) below.

$$V_{relay}(t) = \frac{\cos(\omega t)}{\omega^2 L_S C - 1 + \omega^2 L_L C} + \frac{\cos(\omega t)\omega^2 L_L C}{\omega^2 L_S C - 1 + \omega^2 L_L C} + \frac{L_S C\cos\left(\frac{t}{C^{1/2}(L_S + L_L)^{1/2}}\right)}{\omega^2 {L_S}^2 C^2 + 2\omega^2 L_S C^2 L_L - L_S C - L_L C + \omega^2 {L_L}^2 C^2}$$

(3)

$$I_{relay}(t) = \frac{Cw\sin(\omega t)}{\omega^2 L_S C + \omega^2 L_L C - 1} - \frac{C^{3/2}\sin\left(\frac{t}{C^{1/2}(L_S + L_L)^{1/2}}\right)}{\omega^2 {L_S}^2 C^2 + 2\omega^2 L_S C^2 L_L - L_S C - L_L C + \omega^2 {L_L}^2 C^2}$$

(4)

It can be seen that there will be two frequencies present in the voltage, and the same two frequencies present in the current. These radian frequencies are the power system frequency ω, and $\frac{1}{C^{1/2}(L_S + L_L)^{1/2}}$, the other frequency. This formula of course is a version of the well known $1/(LC)^{1/2}$ describing the natural frequency of any resonant series L-C circuit. Given typical values of line impedance and percent compensation ranging from 50 - 100% it can be quickly determined that the alternate frequency component will always be at a lower frequency than the 60Hz power system frequency.

ω_0 = 60Hz component (in Radians)

ω_1 = alternate frequency component

$$j\omega_0 L \geq \frac{j}{\omega_0 C}$$

$$\omega_0^2 \geq \frac{1}{LC}$$

$$\omega_0 \geq \frac{1}{\sqrt{LC}} \qquad \frac{1}{\sqrt{LC}} = \omega_1$$

$$\omega_0 \geq \omega_1$$

Thus we can conclude that when conditions are normal, and usual levels of series compensation are applied to a transmission line, the alternate frequency generated will be below 60Hz and thus we will call continue to call it the “subsynchronous frequency”.

2.3 What is Necessary to Detect the Subsynchronous Component?

As in most computer based relay algorithms, this paper will suggest use of the Fourier Transform in order to measure different frequency components in the voltage and current signals. However, since there is significant interest in frequency components from DC through the ninth harmonic, use of the FFT is recommended instead of the DFT which is normally used in fundamental frequency relaying applications.[3] The problem of course lies in detecting the correct magnitudes of these components and the correct frequency of the subsynchronous component given a relatively short data window to work with. Of course if one would like to detect at 30Hz intervals it would be necessary to have two cycles of 60Hz input data. If you would like to examine values at 15Hz intervals you would need 4 cycles of 60Hz data. Let us assume for now that there are six cycles of test data available starting at the instant of fault inception. Therefore, using a standard FFT, a magnitude for each frequency is available at 10 Hz intervals starting at DC or 0Hz. Of course there is no problem to speak of if the subsynchronous frequency in question is either 10, 20, 30, 40, or 50 Hz exactly, but this is highly unlikely! If the frequency falls somewhere in between these values, there is no way to tell from the raw FFT result what the correct magnitude or frequency is. Further, if the value is close to 60Hz, there is a corruption in the 60 Hz component thus destroying the accuracy of its magnitude estimate as well.[3]

The proposed solution to these problems consists of several steps. First, to accurately detect the magnitude of the 60 Hz component, an estimation of the error coming from the other terms must be made. This estimation is based on a curve fit to the magnitudes present at other frequencies. Once the 60Hz magnitude is properly determined, it should be removed so that the spectrum includes only the subsynchronous frequency component. Finally, the size of the data window is reduced, point by point, in order to “focus” in on the correct value. This is done repeatedly until the stopping point is reached. The stopping point is determined to be reached at that length of data window which produces one single spike of significant magnitude in the spectrum obtained with the reduced window. This process will be more fully explained in chapter three along with the discussion of the algorithm proposed for solving this problem.

2.4 What is Necessary to Actually Compute L and C Values?

Once the values of voltages and currents have been correctly determined at the fundamental frequency (60 Hz) and at some subsynchronous frequency, then it is a simple matter of solving the equations which describe the model. Recall that the model of the line being used is a simple series L and C. If we consider looking into the system from the terminals of the relay, the impedance would be:

$$X = \omega L_L - \frac{1}{\omega C} \tag{5}$$

Now, this expression can be written twice, once at the power system frequency, and once at the subsynchronous frequency. Using subscripts B and A respectively to describe the two components:

$$X_A = \omega_A L_L - \frac{1}{\omega_A C} \tag{6}$$

$$X_B = \omega_B L_L - \frac{1}{\omega_B C} \tag{7}$$

Solving equations (6) and (7) for C, the result is:

$$C = \frac{1}{\omega_A{}^2 L - X_A \omega_A} \tag{8}$$

$$C = \frac{1}{\omega_B{}^2 L - X_B \omega_B} \tag{9}$$

Equations (8) and (9) are set equal to one another and then L is solved for:

$$L = \frac{X_A \omega_A - X_B \omega_B}{\omega_A{}^2 - \omega_B{}^2} \tag{10}$$

Solving in similar fashion for C we find:

$$C = \frac{\dfrac{-\omega_B{}^2 + \omega_A{}^2}{\omega_A{}^2 \omega_B{}^2}}{\dfrac{X_A}{\omega_A} - \dfrac{X_B}{\omega_B}} \tag{11}$$

Therefore, once values have been computed for the voltages and currents, we take their ratios in order to yield a 60Hz impedance, and a subsynchronous impedance. The imaginary part (since we are neglecting resistance) of these impedances is then put into equations (10) and (11) along with the appropriate frequency values and the series L and C of the line are calculated.

Chapter 3 - Designing an Algorithm – Improved Accuracy for Phasor Computations in the Dual Frequency Post Fault Environment

In this chapter we will consider the design of an algorithm to be used for the computation of series inductance and capacitance of a transmission line as seen from the terminals of a distance relay.

3.1 Discussion of the Challenges faced in Finding a Solution

Again the limitations of the Fast Fourier Transform must be considered as well as how these limitations will effect the solution. Further, the available means to get around these problems must also be examined. As mentioned previously, when there is frequency content in the signal which does not fall directly on the fundamental or one of its submultiples or harmonics, there is a corruption of all neighboring values in the spectrum obtained using an FFT. This is of particular concern in this application as the solution deals with a signal containing very closely spaced frequency components. For instance, typical values could be a 60Hz fundamental frequency with a 45Hz-55Hz subsynchronous value. In this case, if both signals have a true value of 100, we can see that a 45Hz signal adds or takes away an error of greater than 10% from the magnitude of the 60Hz component. When this is added to error in other steps of the solution, it is not surprising that the results would be very inaccurate.

Even after this problem is solved, there is still the question of how to deal with the problem of determining the correct frequency and magnitude of the subsynchronous component of the signals. Here we must try to detect a component whose frequency may be located at a point of high attenuation on the frequency response plot of the particular FFT we are calculating. Quite a few frequency components that are not present in the actual signal will show up as a result of corruption, and the raw FFT result will be practically worthless for determining the magnitude or frequency of this component.

3.2 Curve Fitting to Determine Corruption in 60 Hz Component

In order to remove corruption of the fundamental frequency component (60Hz) caused by the subsynchronous component, it is necessary to make an estimation of what the corruption in the fundamental is so that it can be removed. Let’s consider again the spectrum of the 45Hz and 60Hz combined signal shown in figure 3.2.1.

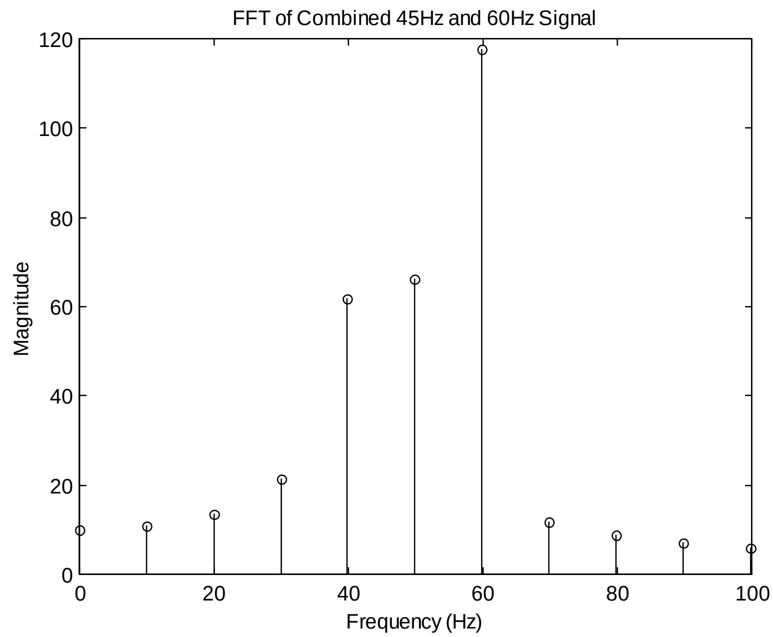


Figure 3.2.1 - 45Hz and 60Hz combined signals

It should be noted right away that the picture is a little more complicated than this, since this is only the magnitude spectrum. There is also a spectrum of phase angle which must be considered. However, for the moment if we just consider the magnitudes, we would like to know the portion of the *computed* 60Hz component which is not attributable to the *actual* 60Hz component. In other words, we seek to determine the amount of “corruption” which has been introduced into the computed result. Since 60Hz is the fundamental frequency for the given FFT, the entire 60Hz portion of the signal (plus the corruption term) is represented in the magnitude seen at 60Hz in figure 3.2.1. Further, the 60Hz portion of the signal contributes no corruption to any other magnitude appearing on this plot. Therefore, the idea used to solve this portion of the problem is simple. Use a high order curve fit to estimate the contribution from the subsynchronous frequency at 60Hz. To do this successfully, we should use only points which appear **above** 60Hz. There are two reasons for this. First of all, we can not make use of the 60Hz value since its composition in terms of the percentage attributable to 60Hz signal versus the percentage attributable to subsynchronous signal is not yet known. If we consider the shape of a pure 45Hz signal as shown below, we know that it has a sharp peak or discontinuity at the spot where 45Hz would be if it were one of harmonic frequencies of the 384 point FFT in question.

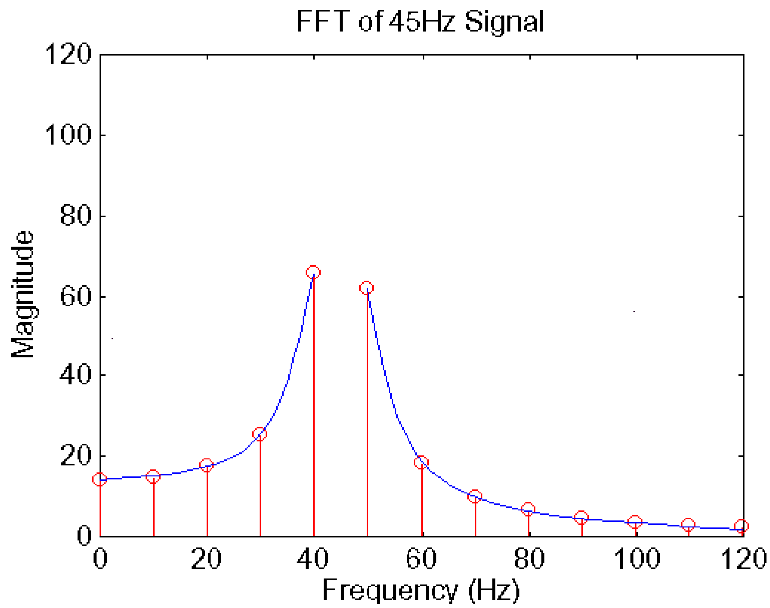


Figure 3.2.2 - Spectrum of 45Hz signal from a 0.1 sec (6 cycles of 60Hz data) data window

Since the shape of the curves resembles the peak of a sharp mountain with a discontinuity at the tip, it is clear that the two sides must be described by different equations. We are uncertain in general what the value of the subsynchronous frequency will be therefore we are best off using points above 60Hz for the curve fit. This way it is possible to get quite a few points to make a good fit.

As mentioned earlier, the picture is a little more complicated since we must consider both the real and the imaginary parts of the FFT result. Therefore, first an initial FFT is run and separated into real and imaginary parts. Then a curve fit is made to each part separately using the 70Hz, 80Hz…110Hz, and 120Hz components to predict the false 60Hz component. Once the complex value of the 60Hz error term is known, it can simply be subtracted from the original FFT result for the 60Hz component, and the true value of the 60Hz component is then known.

3.3 Point by Point Reduction of the Data Window

To decide if a capacitor is present in the system, is a valuable piece of information. To determine if it was part of the fault loop is also valuable. One clue is to search for a subsynchronous frequency of significant magnitude and thus conclude that there was in fact series C switched in at the time of the fault. However, this is not too helpful in the case where more than one series capacitor is installed on a line or when there is some other significant source of capacitance. In these cases, it is important to closely estimate the actual capacitance present in order to make an accurate relaying decision. If we wish to know the actual L and C values present, we must find the correct magnitude and frequency of the subsynchronous component. Once the true 60Hz magnitude has been found (as described in section 3.2), we wish to replace the value at 60Hz with the value of the corrupting component computed by using the curve fit. Therefore we have in essence removed the fundamental 60Hz component and are left with the spectrum of only the subsynchronous component similar to what is shown in figure 2.2.2. Now we must perform an inverse FFT on this corrected data in order to get a set of data points in the time domain. Now the key to the solution is to vary (shrink) the size of the data window one point at a time starting with the entire data set. At each successive reduction in window length an FFT is performed. When finished, each picture is compared and the stopping point which is correct is the window length for which an FFT calculation yields a sharp contrast between the peak value and the next adjacent value in the resulting spectrum. This is known to be the point at which the data window corresponds exactly to one or more periods of the actual frequency because here there is no "leakage" in the adjacent terms.[3] When there is no leakage from other components the window is the correct length for the Fourier Transform to detect the magnitude of the subsynchronous signal. And of course knowing the window length for which this occurs allows us to infer the frequency of the signal we are measuring.

3.4 Flowcharting the Possible Approaches

The exact method described above is actually "approach 2", the method which was found to work more accurately for reasons to be discussed in this section. Figures 3.4.1 and 3.4.2 are flowcharts showing a comparison of two possible methods. Both approaches begin by sampling the voltage and current data from the test system (in the case being examined here we are starting out with 64 samples per cycle). Next an initial FFT is performed. The resulting solution vector is split into real and imaginary parts, and then a curve fit is used to predict the corruption in the 60Hz component resulting from the subsynchronous component. This is done for both the real and imaginary parts of the FFT result separately. Next, the estimated corruption is vectorially subtracted from the original 60Hz FFT result. This produces the correct 60Hz magnitudes for the real and imaginary components.

The next step is where the big difference between the two methods lies. The first approach, depicted in figure 3.4.1, makes use of the corrected 60Hz result to compose a waveform of sample points to emulate the 60Hz component of the initial signal. This synthesized signal is then subtracted, point by point, from the original input signal yielding a vector which should describe only the subsynchronous portion of the original signal. In the second approach, depicted in figure 3.4.2, instead of using the corrected 60Hz result, the algorithm replaces the 60Hz result in the original FFT with the result from the curve fit. Since the 60Hz signal causes no corruption in the other frequency ranges of the FFT result, the new FFT result vector describes only the spectrum of the subsynchronous frequency. Next, an inverse FFT is applied to this vector and the result is a set of data points representing only the subsynchronous frequency content of the original signal.

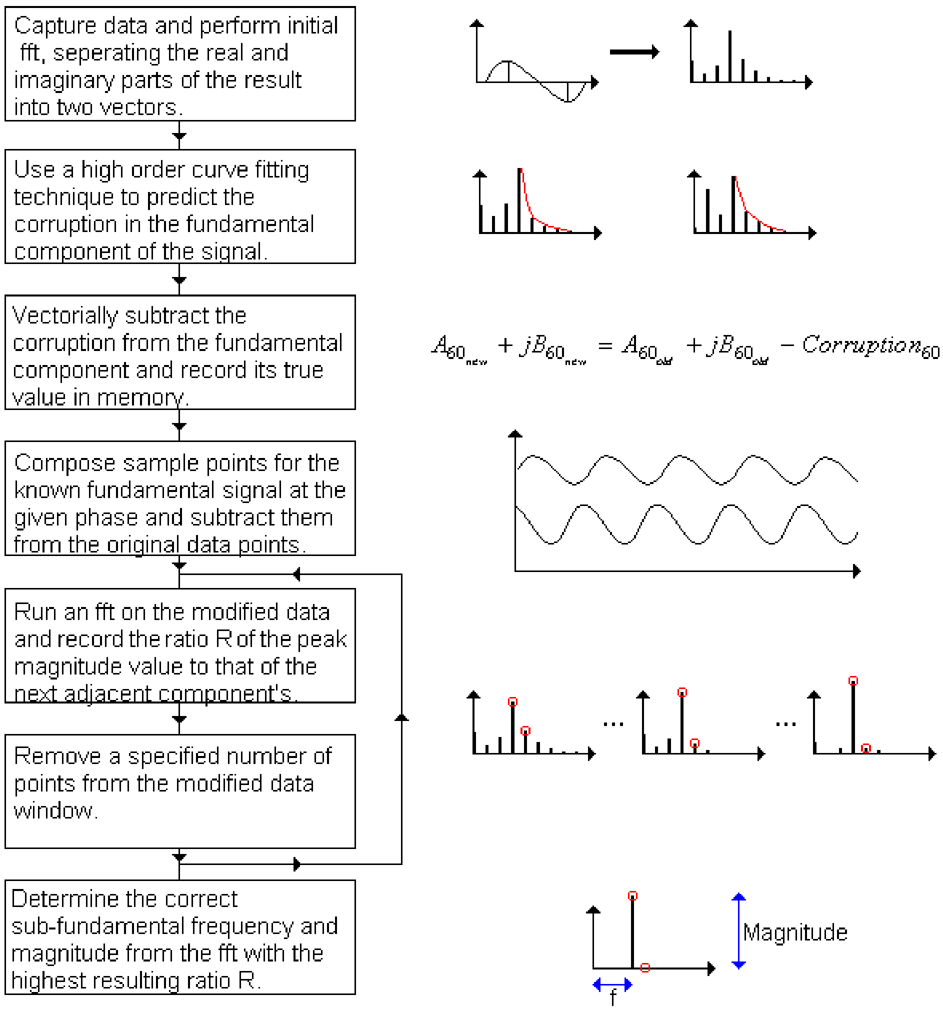


Figure 3.4.1 - Flowchart of Possible Approach 1

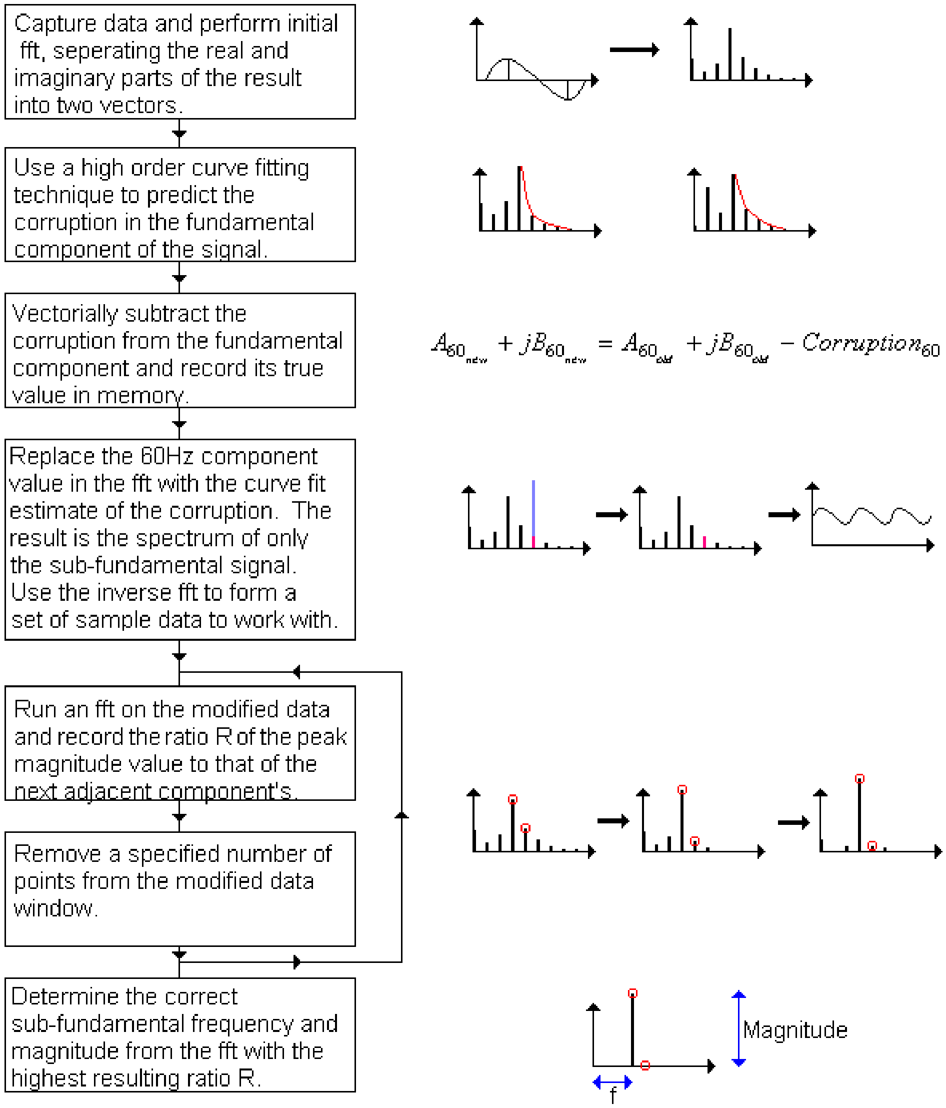


Figure 3.4.2 - Flowchart of Possible Approach 2

In theory both techniques should produce the same solution. However the results obtained using the second approach seem to be much better. The reason for this likely lies in the relative numerical stability of these two approaches. More precisely, the relative magnitudes of the fundamental frequency component as compared to the subsynchronous frequency component. Since the fundamental is much larger in magnitude in most practical cases, it is better to focus on the lower frequency (the subsynchronous frequency) when creating a signal with no remaining 60Hz component. If we subtract points, and there is a slight error in estimation of the 60Hz, this will translate into a large error when compared to the considerably smaller magnitude low frequency component. However if a slight error is made in the 60Hz calculation while creating the frequency spectrum of the subsynchronous, the resulting error will be small compared to the value being sought. In short, when using approach number one and attempting to "remove" the 60Hz by subtracting points, rather than directly constructing the spectrum of the low frequency and working backwards, the remaining "residue" of the 60Hz component tends to be quite large and destroys the integrity of the much smaller subsynchronous signal.

3.5 Design of the Most Efficient Algorithm for Relaying Purposes

As is obvious at this point, the computations being described here are quite numerically intense, particularly for a relay which must act swiftly to protect the system in case of a fault. Therefore it is important to remove all unnecessary steps from the computation and generate the most efficient algorithm possible in order for this approach to have future practical application.

The first question to consider is removal of as many FFT computations as possible. These computations take a significant period of time to complete. For every fault there is one voltage and one current signal which must be analyzed for both 60Hz component magnitude, as well as subsynchronous component frequency and magnitude. This means quite a few FFT's must be computed. Therefore it is important to calculate only the bare minimum necessary.

First of all, the worst computation is the series of FFT solutions necessary to determine the frequency of the subsynchronous component. It can be seen experimentally that the same frequencies are present (while of course in different magnitude) in the voltage and current signals for a given fault. Further, all affected phases' voltage and current signals will also contain the same set of frequencies. Therefore, we conclude that it is only necessary to determine the frequency of the subsynchronous component once for any given fault. The correct data window length, known to "focus" on this component, is then automatically prepared for all other signals which must be broken down to analyze whatever type of fault is in question.

Another way to speed up this same part of the algorithm is to reduce the total number of times the algorithm removes a point from the data window and recomputes the FFT. There is some sacrifice in the accuracy of the result, however this can be kept to a minimum when the maximum number of points to remove from the initial window is chosen wisely. The safest way to go is in steps of two points. This cuts the number of FFT computations in half while also insuring that the FFT is always computed with an even number of points. In general, the FFT will produce erroneous results when a computation is made on a window with an odd number of points.

Another time savings is achieved by using fewer cycles of post fault data. For purposes of testing the validity of the algorithm presented here, six cycles of post fault data have been used. This would only be acceptable for zone two or three protection. For practical zone 2 (and zone 1) use, the algorithm should be reduced to a 4 cycle algorithm. This does introduce some error, however the results are not severely impacted and the relay should still make accurate enough relaying decisions.

3.6 Test of the Single Phase Algorithm

In order to determine if the logic implemented is correct, several tests were performed. The following are results of several tests demonstrating the successful use of the above described algorithm.

First of all, the simple test case described in section 1.1 was implemented in the EMTP (Electromagnetic Transients Program) which is available from the Electric Power Research Institute (EPRI). The input file for the study is shown in figure 3.6.1.

```
BEGIN NEW DATA CASE
C ----dt<---Tmax<---Xopt<---Copt<-Epsiln<-Tolmat<-Tstart
26042e-8    0.1     60     0.
C .....^.......^.......^.......^.......^.......^.......^
C -Iprnt<--Iplot<-Idoubl<-Kssout<-Maxout<---Ipun<-Memsav<---Icat<-Nenerg<-Iprsup
      1       1       0       1       0       0       0       2
C .....^.......^.......^.......^.......^.......^.......^.......^.......^.......^
C <--Isw<--Itest<--Idist<--Aincr<-Xmaxmx<-Degmin<-Degmax<-Statfr<-Sigmax<--Nseed
C
C .....^.......^.......^.......^.......^.......^.......^.......^.......^.......^
C --Kchg<---Mult<---Kchg<---Mult<---Kchg<---Mult<---Kchg<---Mult<---Kchg<---Mult
C
C .....^.......^.......^.......^.......^.......^.......^.......^.......^.......^
C <---Nodes--><---Refer--><-Ohms<---mH<---uF<-------------------------OutputÄÄÄ¿
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C                          V
  POS   SW1             3.                                  1
  SW2                6.  596.                             1
BLANK END OF CIRCUIT DATA
C <-Bus1<-Bus2<---Tclose<----Topen<-------Ie<----Flash<--Request<-----Target<--O
  SW1   SW2     1e-9      1.                                  1
```

```
  C .....^.....^.........^.........^.........^.........^.........^...........^xxx^
BLANK END OF SWITCH DATA
C <--Bus<I<-----Ampl<-----Freq<----Phase<-------A1<------T1><---Tstart<----Tstop
14   POS        100      60.0       0.0                         -3.        1
C .....^.^.........^.........^.........^.........^........^..........^.........^
BLANK END OF SOURCE DATA
C
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
POS   SW1   SW2   SW3
C .....^.....^.....^.....^.....^.....^.....^.....^.....^.....^.....^.....^.....^
BLANK END OF OUTPUT REQUEST
BLANK CARD ENDING PLOT CARDS
BLANK END OF DATA CASE
BLANK END OF ALL CASES
```

Figure 3.6.1 - EMTP Test file to validate single phase case.

In order to analyze the numerical results from the EMTP test case, the algorithm described in the last two chapters was converted into a MATLAB version 5.1.0.421, “M” file. MATLAB is a computer software package, available from The Mathworks Inc., which is well suited to numerically intense computations. The preprogrammed functions in MATLAB are numerically stable and easy to use. Therefore, MATLAB makes a convenient tool for testing the validity of potential algorithms.

The results from the Matlab implementation of the described algorithm are as follows:

X_C=4.452Ω and X_L=6.018Ω   for actual values of X_C=4.444Ω and X_L=6Ω

$F_{subsynchronous}$=40.2Hz $F_{subsynchronous}$=40Hz

In the case above, the subsynchronous or low frequency value was deliberately set to be one of the natural frequencies of a 6cycle 60Hz fundamental FFT. Next, the values were changed so at to produce a non-subharmonic frequency for this particular FFT.

X_C=2.738Ω and X_L=3.093Ω   for actual values of X_C=2.653Ω and X_L=3Ω

$F_{subsynchronous}$=37.3Hz $F_{subsynchronous}$=36.9Hz

Again, the results tend to be quite close to the actual system values. Another check is to view the magnitudes of V and I at the subsynchronous frequency and compare them to the predictions of equations (3) and (4). This check also confirms that this algorithm has computed correct results. A series of tests were performed including a number of tests on more complex single phase circuits with shunt capacitance and series resistance added, and the results were all in support of the assumption of a properly implemented, correct procedure. These test results are shown in Appendix B. Detailed testing of the algorithm is also conducted in section 5.1. There, a three phase application of this algorithm is tested with a pi modeled transmission line.

Chapter 4 – Application to a Three Phase System

All useful algorithms must be applicable to a real world system. With this in mind, steps are taken in Chapter 4 to apply the theory of Chapters 1,2, and 3 to a realistic three phase transmission line.

4.1 Differences Between Single Phase and Three Phase Systems

Of course there is the obvious difference between single and three phase systems, which is the addition of the other two phases! With a single phase system, there is only one impedance value which is pertinent to each line, capacitor, and load. With a three phase system, there are however ten different types of possible faults. In three phase systems it is best to consider the symmetrical component representation of each fault. The positive, negative and zero sequence impedances of a three phase system interact in different ways depending on the operating state of the system. This operation state could be a balanced no fault condition, or it could be operation amidst a host of different fault types, each producing differently connected networks of the three sequences. It is for this reason that the picture becomes far more complicated when moving from a single phase case to a three phase case.

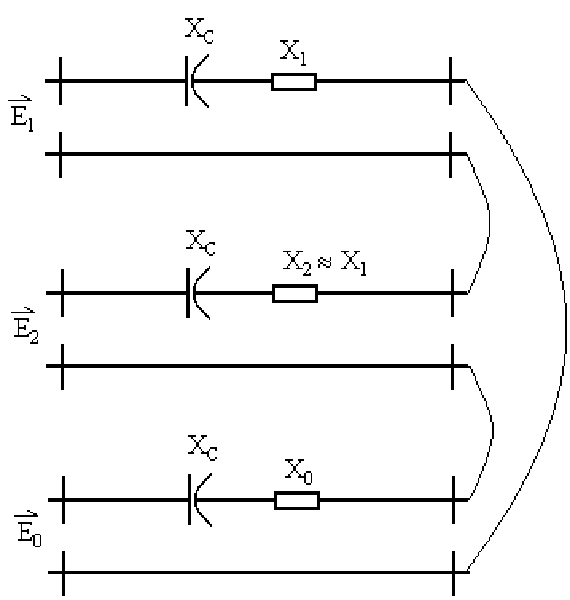


Figure 4.1.1 - ϕ-G Fault Symmetrical Component Network Connection

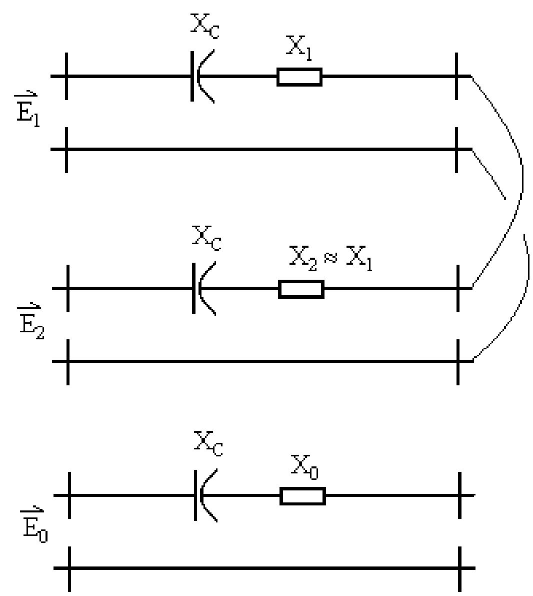


Figure 4.1.2 - ϕ-ϕ Fault Symmetrical Component Network Connection

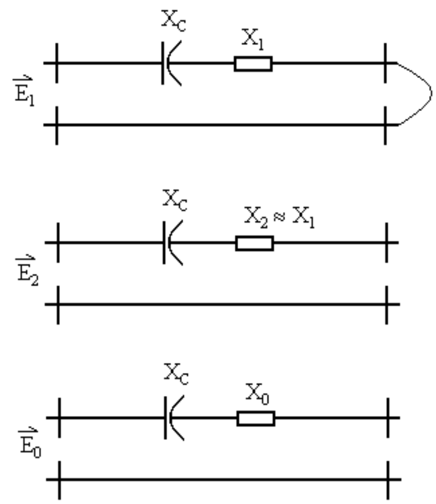


Figure 4.1.3 - 3ϕ Fault Symmetrical Component Connection

Now let us consider more specifically how these complications will effect the picture of series L and C of each individual phase, as seen by the relay. First of all, as mentioned previously, we have determined that the same set of frequencies are present in the voltage and current signals pertinent to any given fault impedance calculation. And fortunately, the frequency signature of the zero sequence current, in the case of phase to ground faults, matches that of the voltage and current for the faulted phase as well.

4.2 Three Phase System with Series Capacitance

For our purposes, an assumption is made, that the fault type is known. It can be imagined as another stage in a traditional digital distance relay after fault detection and classification has already been taken care of. The modifications necessary for conversion to a three phase system are dependant on the type of fault that you are dealing with. Of course for the case of a three phase fault, any phase voltage can simply be divided by the respective phase current to determine the impedance to the fault, thus calling for no change whatsoever. Things are almost as simple for ϕ-ϕ or ϕ-ϕ-g faults. Here, once the fault type is known, the difference between the two affected phase voltages serves as the necessary voltage, and the difference of the corresponding phase currents serves as the necessary current. Again, a ratio is taken and the imaginary portion of the result tells us the inductive reactance to the fault.

The problem arises when dealing with single phase to ground faults. The method for calculating in a traditional case is to use the formula:[2]

$$Zfault = \frac{V_{phase}}{I_{phase} + (mI_0)}$$

Where I_0 is the zero sequence current equal to one third of the sum of I_a, I_b, and I_c or:

$$I_0 = 1/3*(I_a + I_b + I_c)$$

And where m is a factor given by:

$$m = \frac{Z_0 - Z_1}{Z_1}$$

This is however the expression describing m in a line that does not include series capacitance. The value of m in that case is independent of distance to the fault. However when considering a line with series capacitors installed, the value of m when the capacitor is switched into the line is given by:

$$m = \frac{Z_0 - Z_1}{Z_1 - Z_C}$$

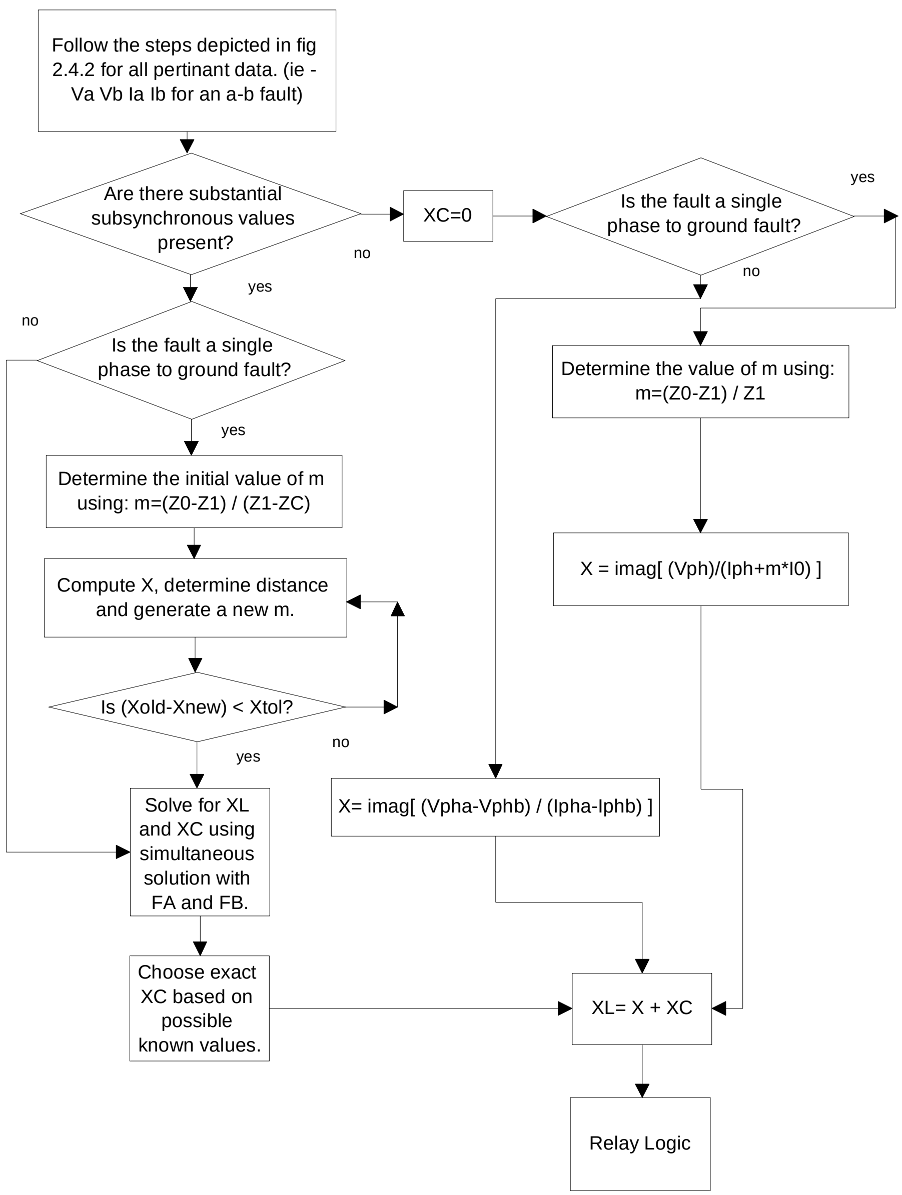
Consequently, the value of m is now based on fault location. Since that is unknown, it becomes necessary to use an iterative type of method to find a solution. The algorithm first examines the frequency signature of the appropriate voltages and currents and looks for subsynchronous values which would indicate that the capacitor was present in the line during the fault. If it does not find these values, it reverts to the traditional method of determining fault impedance. If a strong subsynchronous value is present, then a guess is made for the value of m. This could be based on a fault at say 50% of the length of the line. Then a computation of the fault impedance is made based on this value. The fault impedance found is used to generate a better idea of the actual fault location which in turn is used to generate a new estimate for m. This cycle continues until the change in fault impedance in successive steps reaches a tolerance value.

4.3 Three Phase Algorithm – Flowchart

There are a number of book-keeping tasks involved in the processing of a three phase case. First of all, when inputting data, knowledge of the appropriate fault type allows the program to load only data pertaining to the type of fault at hand. If this fault is a phase A to ground fault for example, the algorithm must recognize this and then load Va, Ia, and I0. Then the program runs through the previously described determination of the synchronous and subsynchronous frequencies and magnitudes present in the various signals.

It is after these steps that the real changes occur. As can be seen in figure 4.3.1, the final steps consist of decisions such as whether or not the capacitor is present in the line based on subsynchronous magnitude of the signals. The other important change is the addition of the logical loop which iteratively determines the correct

value for m if the capacitor is present during the fault. To further increase the accuracy of the solution, we can also insert the correct capacitance value (if the value is constant) once we have determined that the capacitor was Figure



4.3.1 – 3 Phase Logic for Computing X_L After Frequency Analysis switched on. This is allowed for by the assumption that the relay could be preprogrammed with the value of the series capacitance installed on the line at the time of commissioning.

All of the described procedures, following the frequency analysis of the input signals, are shown in the flowchart of figure 4.3.1 on the next page. For verification testing of this procedure, see section 5.1. Tests in that section include 3 phase and phase to ground faults on a pi modeled 3 phase transmission line (see appendix B for single line test system diagram).

Chapter 5 – Additional Considerations of Three Phase Systems

In order for a system model to be accurate in its representation of the actual system, all parameters of significance should be considered. Chapter 5 will look into some other issues such as mutual inductance, shunt capacitance, and the MOV which protects the capacitor itself.

5.1 Addition of Mutual Inductance and Shunt Capacitance

In order to more accurately test the response of the algorithm in a ‘realistic’ setting, the model used in the EMTP simulation should be inclusive of as many of the power line’s characteristics as possible. Now that the algorithm has been tested and seems to function well in the ideal case, we can begin to add more detail to the model. As the detail is added, it is possible to not only test whether the algorithm still functions properly, but also how well it functions based on certain parameters of the system it is applied to. The first addition will be that of shunt capacitance.

All AC transmission lines have shunt capacitance. The longer the line, the more shunt capacitance becomes a factor in simulation and analysis. Failing to account for this in longer lines will lead to increased error in the estimate of fault location made by the relay algorithm.[6] The EMTP model used to emulate the transmission line sections is the “pi Circuit Branch”. The capacitance and inductance data for transmission lines can be calculated using a “line constant” subroutine of the EMTP.

Upon simulating the new system and analyzing the data with the algorithm unmodified, it turns out that the shunt capacitance effect is negligible. Even when the value is increased to roughly twice that of the reasonable estimate based on traveling wave velocity, the algorithm remains robust and continues to return solutions for L and C that are within 5% of the actual values simulated in the EMTP. The “pi” model of the transmission line also includes mutual inductance parameters and is therefore a very accurate model of a real transmission line.

In order to test the three phase system an EMTP simulation was performed on the system using the pi circuit model representation of the transmission line. For the test purposes, a three phase fault has been triggered following 2 cycles of system operation. The output of the EMTP simulation was then exported and converted to a .wk1, or a Lotus 1-2-3 format. Figure 5.1.1 shows the current and voltage waveforms from the B phase.:

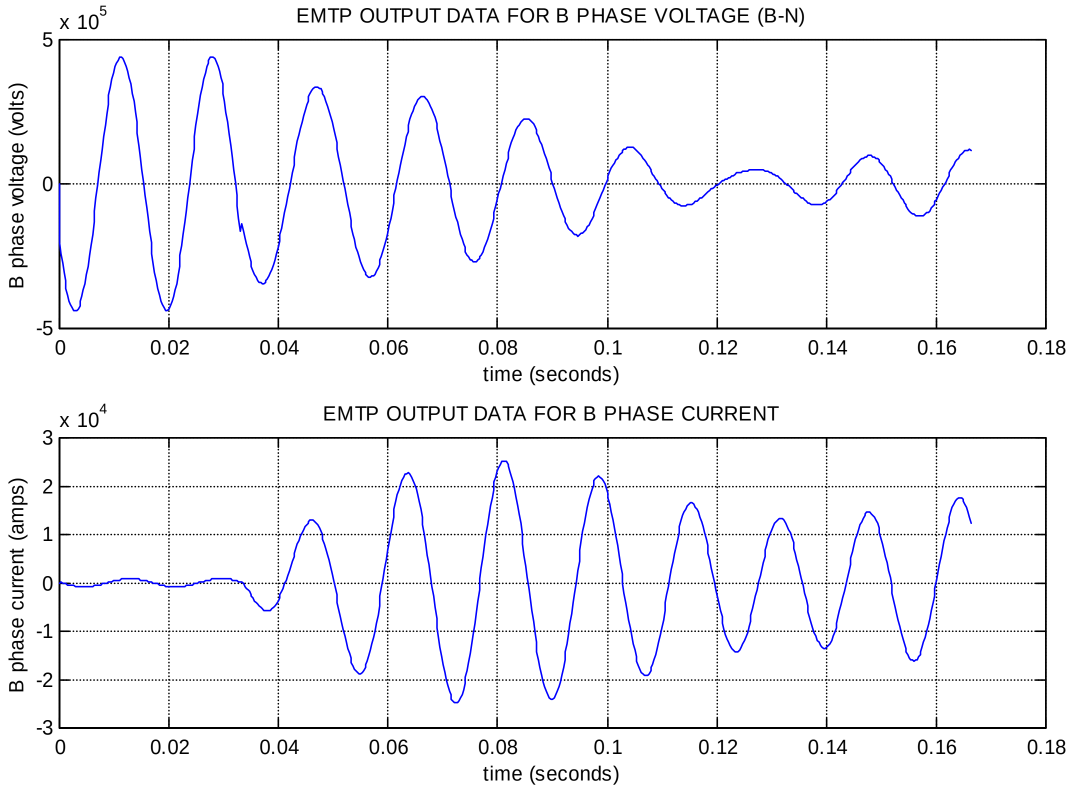


Figure 5.1.1 – Phase B Voltage and Current for a Three Phase Fault

The data points which make up these curves are then converted to the frequency domain by use of the FFT or Fast Fourier Transform. Then, a high order curve fit is used to determine the amount of corruption present in the fundamental frequency component due to the presence of the subsynchronous component. This procedure is completed for the real and imaginary parts of the initial FFT separately. This procedure must then be done a total of 4 times for a V/I pair. One real and one imaginary FFT solution curve fit for voltage, and one real and one imaginary FFT solution curve fit for the current. Figure 5.1.2 shows the FFT results and the curve fit used to predict the corruption in the 60Hz (fundamental) component. In this particular case, note that the corruption has caused a decrease in the real portion of the fundamental component of the current. Therefore, the actual value is higher than the result of the initial FFT would indicate. The opposite is true for the imaginary portion of the current.

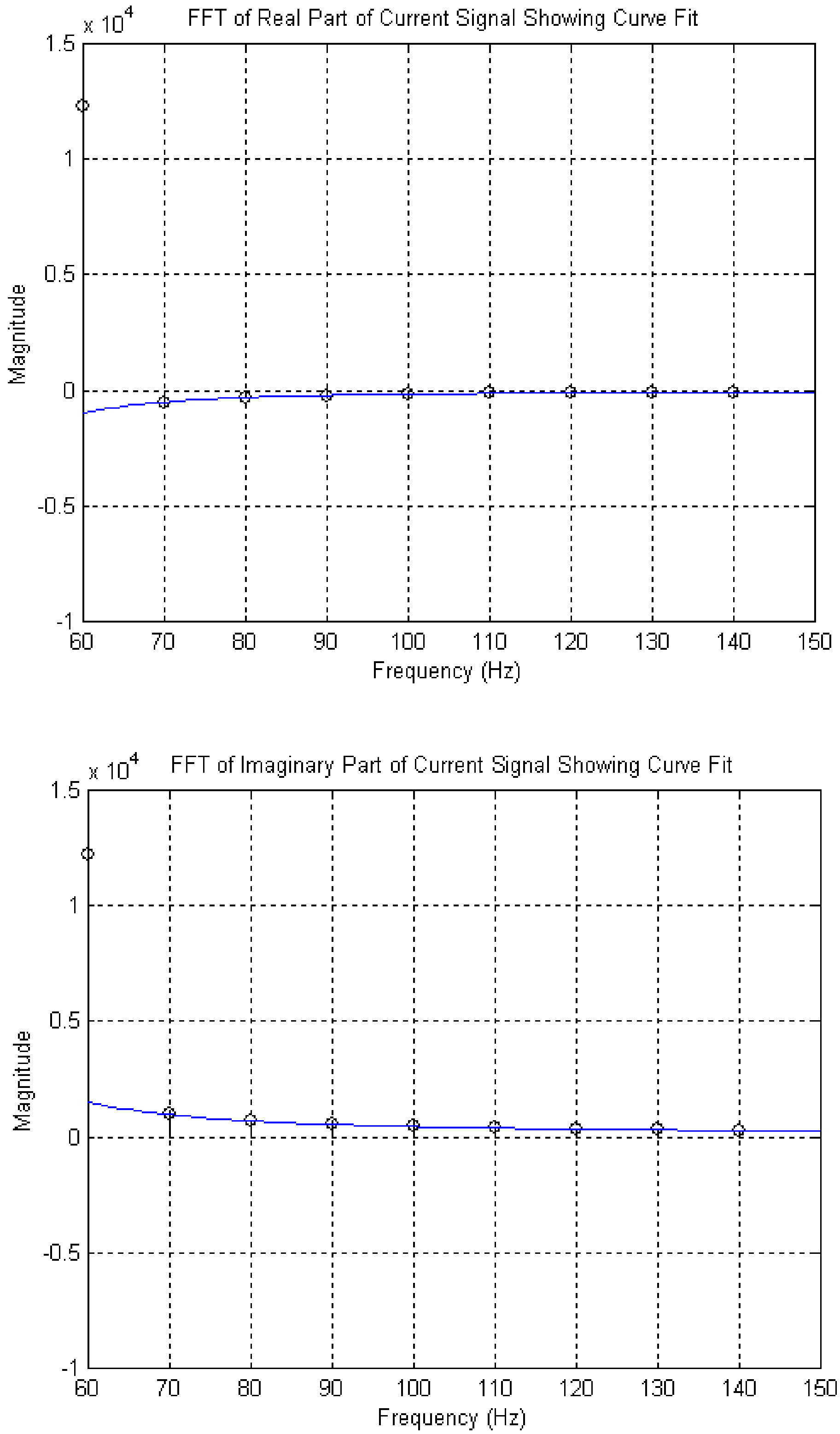


Figure 5.1.2 – Curve Fitting Technique to Identify Corruption in Fundamental Displayed for Current Signal

Once the corruption has been identified, the proper 60Hz magnitude is computed, and the fundamental component of the spectrum shown in figure 5.1.2 is replaced with the curve fit estimate of the corruption. This result will then be a close representation of the spectrum of the subsynchronous frequency component. The only problem with this resultant spectrum is that it has been produced by an FFT which did not have the appropriate data window length in order to address this subsynchronous frequency as a fundamental or submultiple of a fundamental. Figure 5.1.3 shows the spectrum of the subsynchronous component only with quite a bit of "leakage" in the neighboring terms indicating improper window length for the frequency in question.

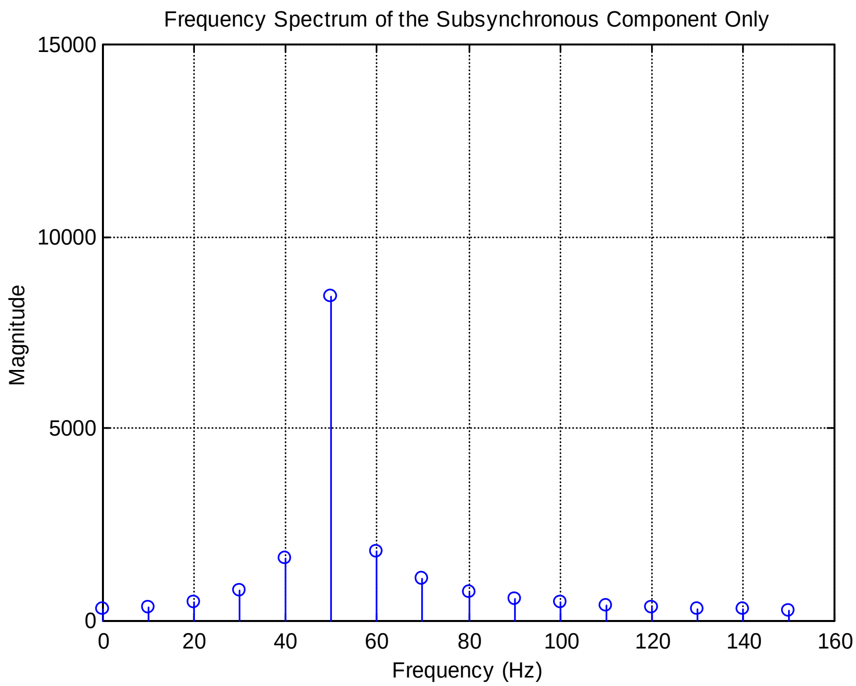
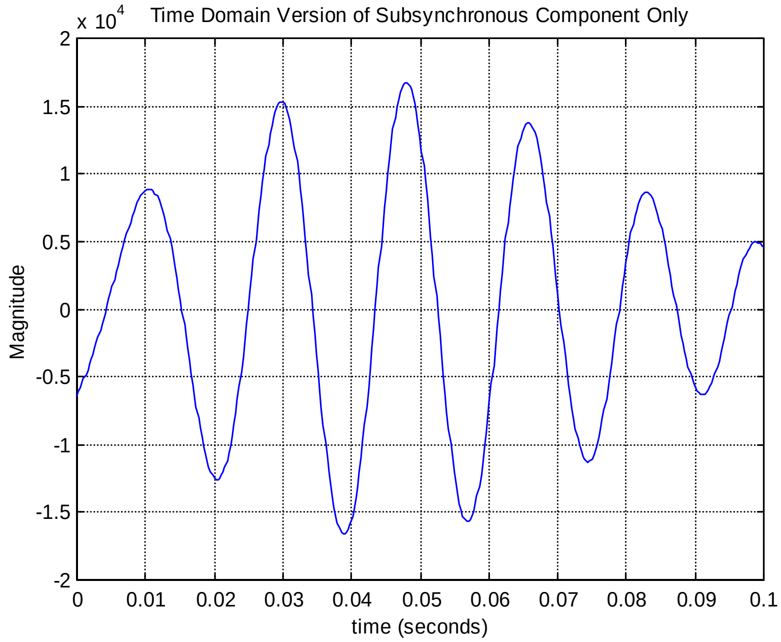
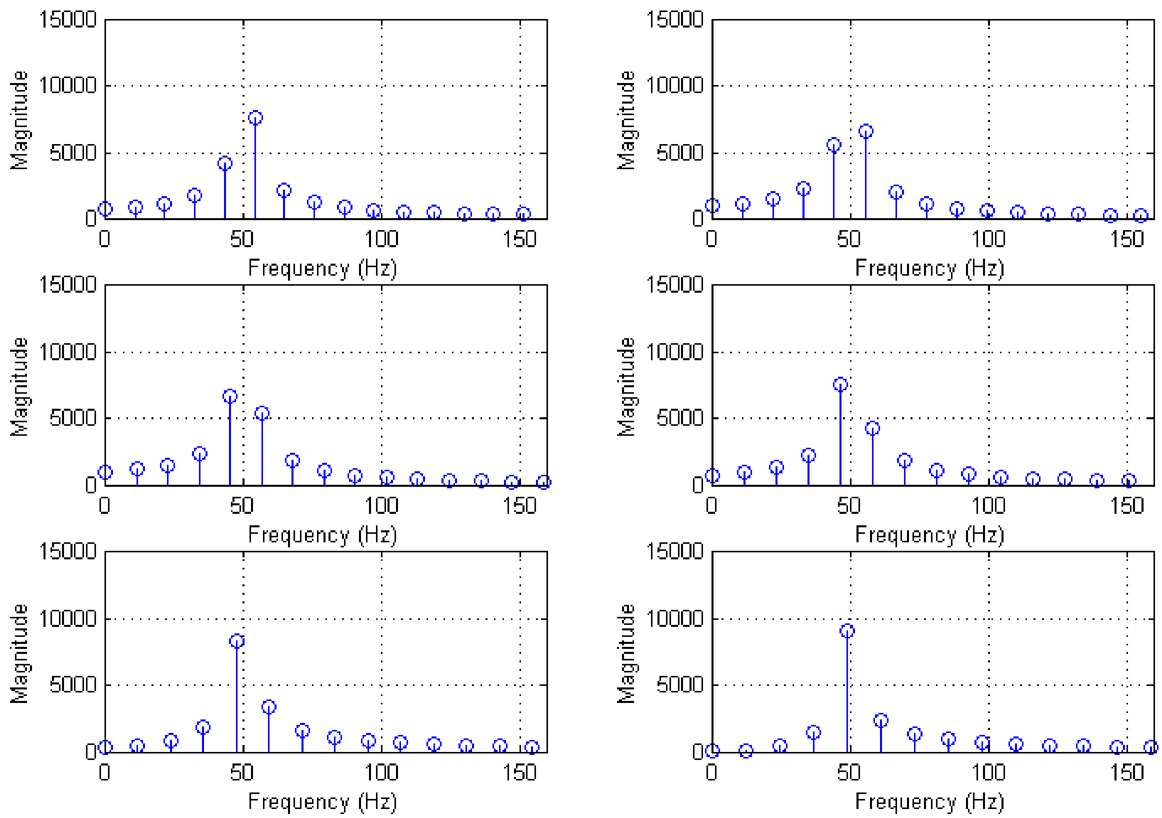


Figure 5.1.3 – Frequency Domain Representation (Spectrum) of the Subsynchronous Component Only

Therefore, in order to determine the proper frequency and magnitude of this subsynchronous component, two steps are still necessary. First, an IFFT (Inverse Fast Fourier Transform) is performed on the spectrum, and the result is a time domain representation of the subsynchronous value. We then vary the window length until the FFT is in "focus" and then record the proper magnitude and frequency of the subsynchronous component. Figures 5.1.4(a) and 5.1.4(b) show the time domain representation, and the procedure of "focusing" the data window to generate a proper spectrum respectively.





Figures 5.1.4 .a (top) and 5.1.4.b – Subsynchronous Waveform and Results of Focusing FFT Window

The appropriate window length is determined by comparing the relative magnitude of the fundamental (largest value seen) to the magnitude of the next adjacent frequency component for each window length. When this ratio is a maximum there is little or no remaining "leakage" and the fundamental frequency component of the signal is now equal to, or an even multiple / submultiple of one harmonics of the corresponding FFT. Therefore, the frequency and magnitude calculated with the FFT for that window length should be correct.

In the example used to test the algorithm, the computed frequency of the subsynchronous component is found to be 49.873Hz. When this value is used and the impedance (V/I ratio) is computed at that frequency, the resulting values for L and C to the fault location are j61.4788 Ω of inductive reactance, and –j64 Ω capacitve reactance. This represents a determination of fault location, for either relaying or fault location purposes, with an accuracy of 97.6%.

In order to verify the process, described in section 4.2 and 4.3, for solving in the case of phase to ground faults, using an iterative approach to find m, the following test was performed. This time the EMTP analysis was performed using a time dependant switch between the A phase and ground. The following graphs (figure 5.1.5) depict the A phase voltage and current through the test.

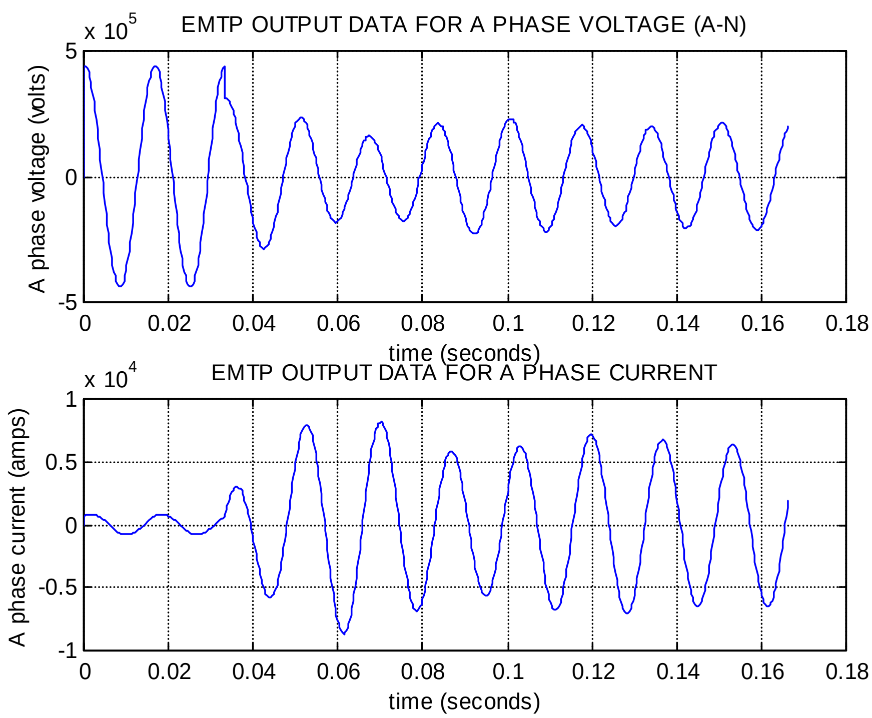


Figure 5.1.5 – Phase A Voltage and Current for an A-G Fault

Again, as in the case of the three phase fault, the data points which make up these curves are converted to the frequency domain by use of the FFT. Then, a high order curve fit is used to determine the amount of corruption present in the fundamental frequency components of the real and imaginary voltage signal as well as the real and imaginary portion of the current signal. Figure 5.1.6 shows the FFT results and the curve fit used to predict the corruption in the 60Hz (fundamental) component. For demonstration purposes, the real and imaginary components of the current signal have been shown. After determining the magnitude of the corruption, the true 60Hz magnitude is found, and the fundamental component of the spectrum shown in figure 5.1.6 is replaced with the curve fit estimate of the corruption. The result is a close representation of the spectrum of the subsynchronous frequency component. Figure 5.1.7 shows the spectrum of the subsynchronous component only with quite a bit of "leakage" in the neighboring terms indicating improper window length for the frequency in question.

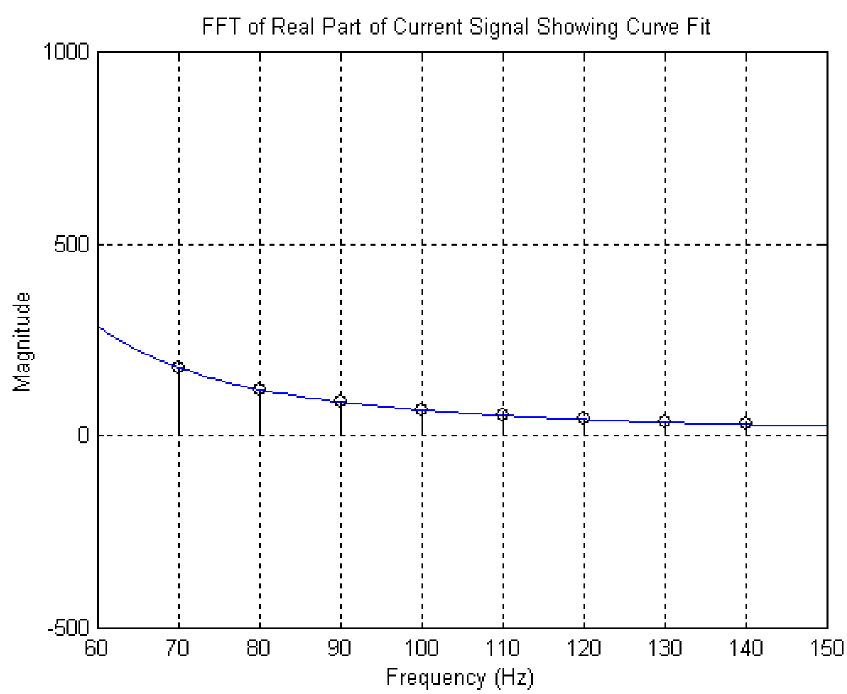


Figure 5.1.6 – Curve Fitting Technique to Identify Corruption in Fundamental of Current Signal

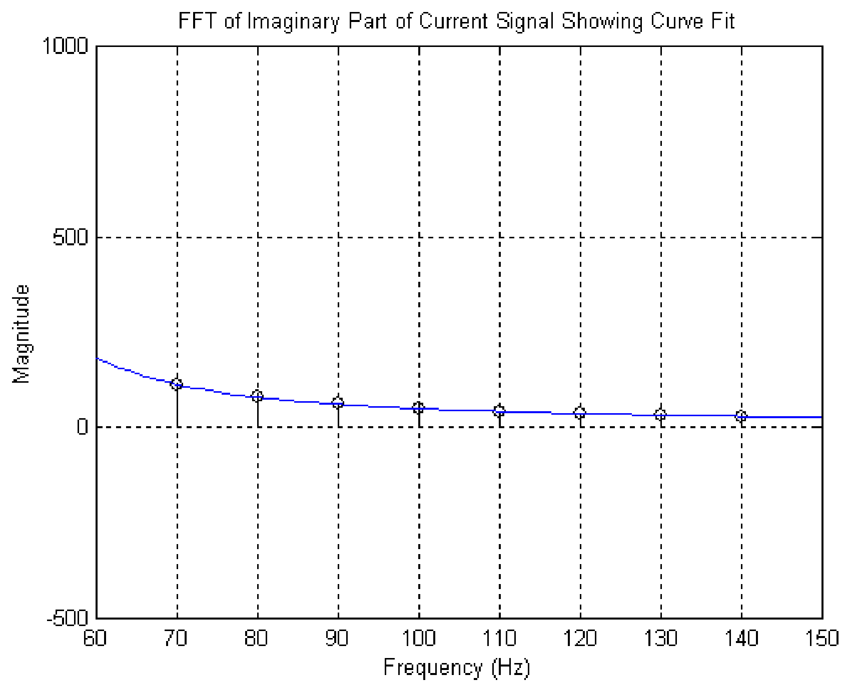


Figure 5.1.6 (Cont'd)

It is then the job of the inverse FFT to generate the series of points which will represent this subsynchronous signal in the time domain. Application of the IFFT to the spectrum shown in figure 5.1.7 produces the waveform shown in figure 5.1.8.

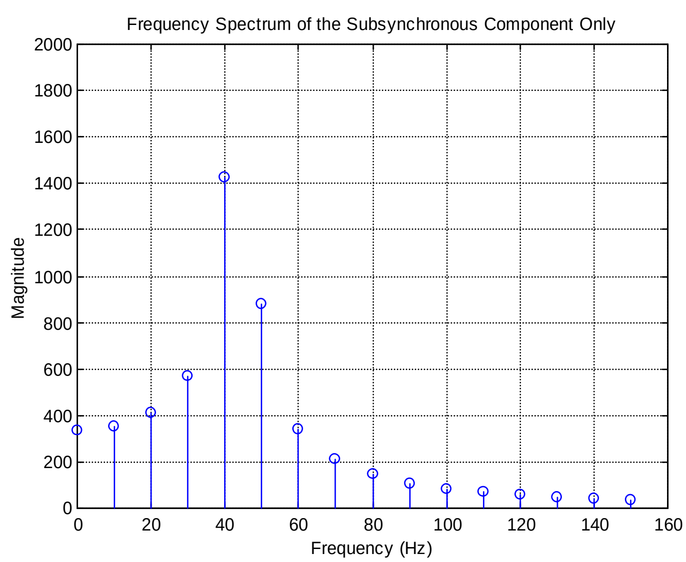


Figure 5.1.7 - Frequency Domain Representation (Spectrum) of the Subsynchronous Component Only

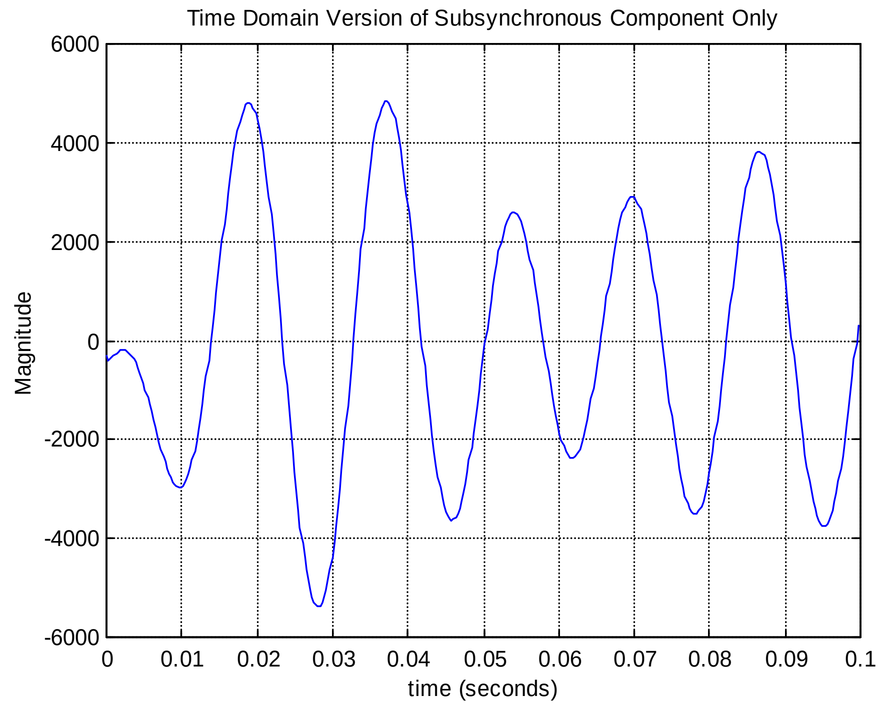


Figure 5.1.8 – Waveform of Isolated Subsynchronous Component

Again, the final step in quantifying the subsynchronous component of the signal is to adjust the window length until the resultant FFT shows the sharpest resolution possible between the fundamental and the adjacent values. Figure 5.1.9 shows this process.

Once the proper values for the magnitude and frequency of the subsynchronous component have been found as well as the proper magnitude of the fundamental, it is then necessary, when working with a phase to ground fault, to compute the compensated current in order to arrive at the value of impedance to the fault. As discussed in section 4.2, in an uncompensated transmission line, the factor "m" is found as follows:

$$m = \frac{Z_0 - Z_1}{Z_1}$$

This works out well since all terms in the equation are based on the line length to the fault, and it is possible to simply use the Z_0 and Z_1 parameters for the entire length of the line. Therefore, the quantity

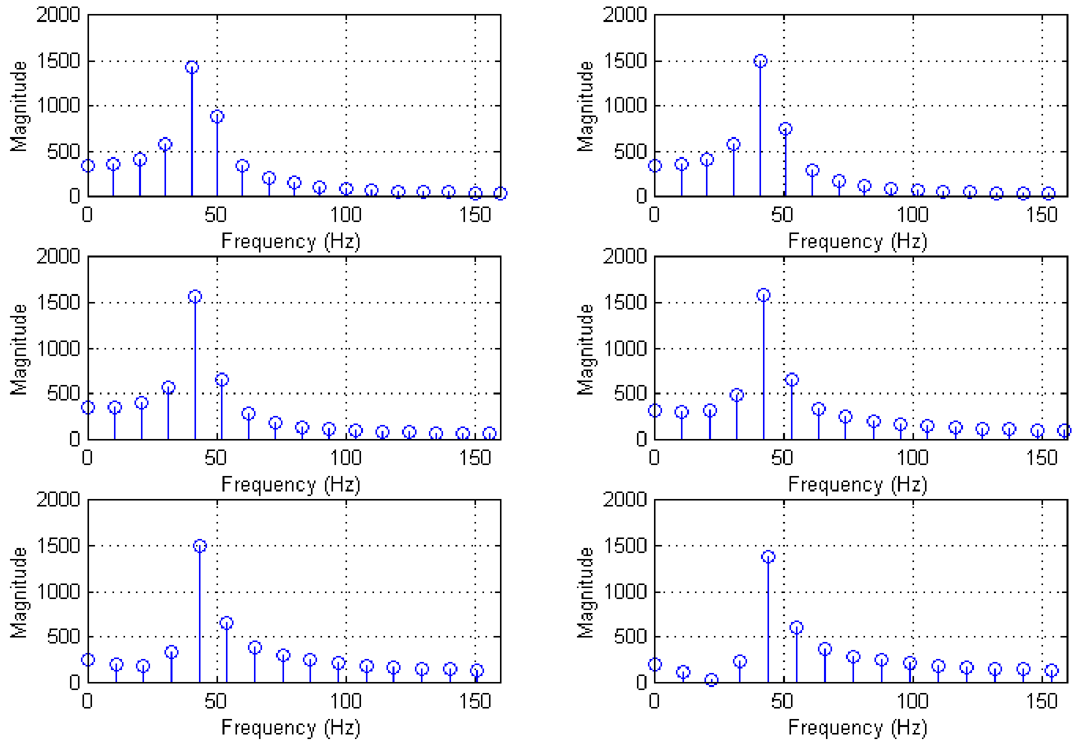


Figure 5.1.9 – Progressive Adjustment of the FFT Window Length

m for an uncompensated line remains constant for a given line and is not dependant on fault location. However, the value of m for a series compensated line is determined using:

$$m = \frac{Z_0 - Z_1}{Z_1 - Z_C}$$

In this equation, the value Z_C (the impedance of the capacitor), which is a constant value regardless of fault location, is in the denominator, and therefore we must revert to using the actual values of Z_0 and Z_1 to the point of the fault. Therefore, m is suddenly dependant on fault location. Since fault location is unknown, we are forced to use an iterative approach to determine a value for m so that we can determine the fault location.

The next challenge in duplicating circumstances which would be seen on an actual transmission line is to add shunt MOV protection to the capacitor. These devices are nonlinear resistive elements which are used to protect ***some*** series capacitors from the high voltages that would be seen across their terminals when there is a fault condition (very high currents).

5.2 Addition of Metal Oxide Varistors in Shunt with the Series C Element

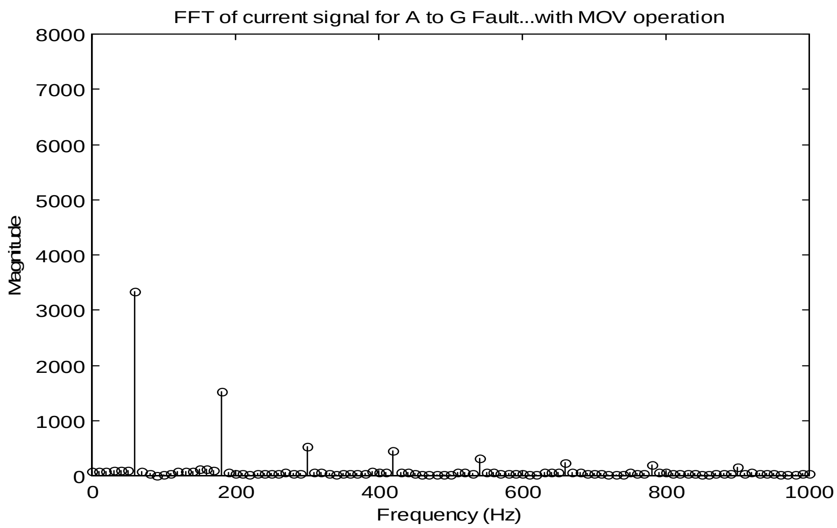
Metal Oxide Varistors are typically placed in parallel with series capacitors.[2] These devices, known as MOV's, are crucial in the protection schemes of these capacitors. When a fault occurs and line current surges to a level significantly higher than normal, damage to the dielectric in the capacitor can occur.[5] The MOV placed in parallel with the capacitor prevents this by acting in a manner similar to a Zener diode.

In the protection of series capacitors, the use of Metal Oxide Varistors (MOV) has become common practice. These devices protect the capacitors by insuring that the voltage across the capacitor does not exceed a certain threshold as might occur during a high current fault.[5] This is accomplished by a device whose terminal characteristics resemble that of a Zener diode. When the voltage is below the threshold, the device has very high resistance. However when the voltage exceeds the level set for the device, its resistance drops very quickly and acts to short the terminals of the capacitor in order to protect the dielectric from the damaging effects of a flashover.

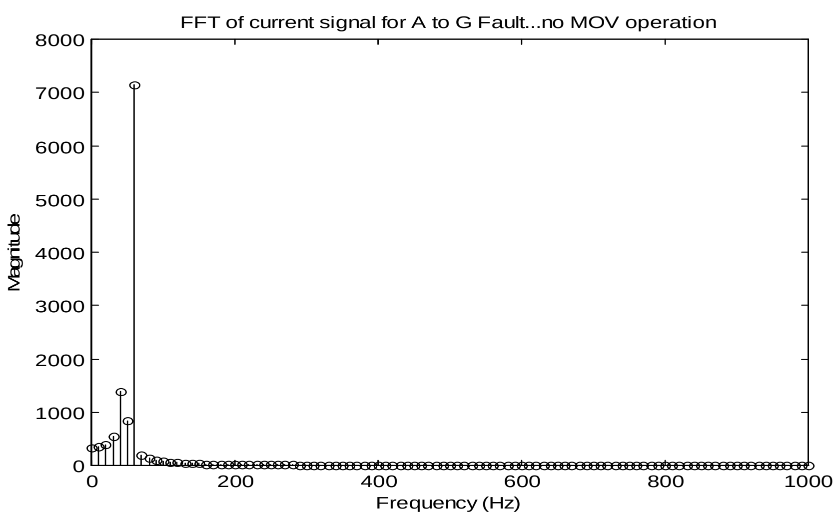
The device however can cause problems due to its highly non-linear nature. The MOV is simulated in EMTP with a "three phase, voltage sensitive, non linear resistance." The resistance of this device will vary as the voltage on the capacitor terminals varies, thus simulating an MOV during a fault. When the set threshold is passed, the MOV model will act to short the capacitor. The addition of this device to the test circuit should produce a highly accurate model from which to collect data.

The problem is that when the MOV does operate, it is very difficult to make any sort of decision based purely on the results of data analyzed using an FFT. This is due to the highly transient nature of the signals as a result of waveform clipping. This results in unreliable computed phasor results. There is however a positive side effect to all of this. When the MOV does operate (keep in mind that not all faults will induce a current level sufficient to pass the MOV voltage threshold and activate the device), it creates a frequency signature which can be positively identified. When there is operation of an MOV, it is obvious that a series capacitor was part of the fault loop since only fault current would cause an MOV to operate and clip the waveforms seen by the relay.

With this in mind, observe the two frequency spectrums below. In the first one, the MOV operated and in the second one, the MOV did not operate.



Clearly, in the case where the MOV did operate, there is a noticeable presence of 3rd 5th 7th and 9th harmonics. By examining the post fault spectral results for the presence of 3rd 5th and 7th harmonics measuring say 5% of the fundamental, it is possible to suggest conclusively that the MOV operated and



thus the capacitor was part of the fault loop. This system would not trigger falsely for events such as transformer inrush and overexcitation since the algorithm would search for content of **all** three harmonics in the signal in order to make a decision. It is also important to exclude the first cycle of post fault data in this analysis. This is due to the fact that we are essentially looking for a step change to indicate MOV operation. Unfortunately, the initial fault inception would appear as a step change as well regardless of MOV operation and could cause erroneous results.

This approach was tested and indeed it was found to produce the correct result (operation vs. no operation) in all cases. As a “double-check”, a computer relay algorithm can also compare the second, third, and fourth post fault cycles of data to one another. It should be seen that a similar magnitude or percentage of harmonic content exists in each in order to issue a confirmation of MOV operation. When this is not seen, it would be logical to conclude that the harmonics seen across the entire averaged 4 cycle window were due to some other step change event such as might be the case in an evolving fault.

Another indicator that may be helpful is to monitor the current in the first two post fault cycles. More accurately, the current magnitude in the first post fault cycle versus the second post fault cycle. Typically, in the case of MOV operation, the first cycle of post fault current is found to have a significantly higher magnitude than the second cycle of post fault current. The reason for this is increasing impedance. As the MOV shorts the capacitor, the compensation of the line is lost, and its total impedance increases thus reducing the fault current. For more thorough tests of this procedure, see Appendix D.

This indicator is more troublesome to implement and is not as clear a warning sign for a number of reasons and therefore was not studied in detail here. There are a number of other variables that will affect the post fault current behavior such as spark gaps, and therefore an algorithm based on this idea would be less robust in a general case.

The next inaccuracy caused by the MOV is a characteristic shift in the resistance seen on an RX diagram. This shift is due to the added series resistance of the line caused by the MOV operation. As mentioned before, the MOV protects by shorting the capacitor to create an alternate fault current path. Therefore, it has a resistance that varies with the intensity of the fault. Since this resistance contributes to the series resistance that would normally be seen at the relay.

The shift in the RX characteristic will be similar to that shown in figure 5.2.1. From this, it could be surmised that if one were able to make an accurate phasor measurement, this information could be used to determine if the series capacitor was involved in the fault or not. More specifically, if the observed impedance phasor fell on the characteristic of the line, it would

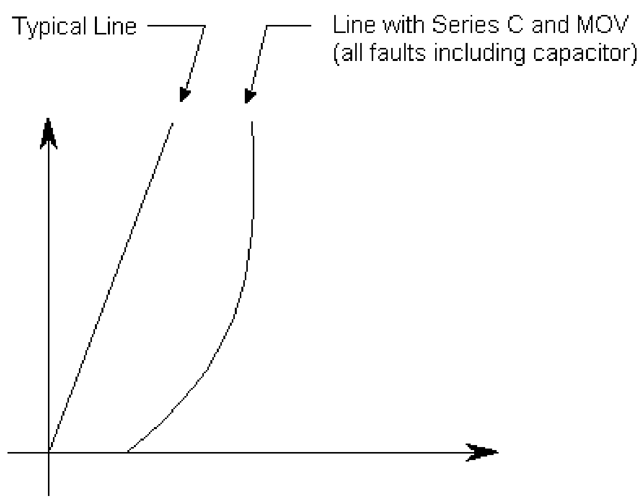


Figure 5.2.1 – RX characteristic shift due to MOV introduced R

be obvious that the MOV did not operate and therefore the fault could be in front of or behind the capacitor. But if the impedance plotted closer to the characteristic on the right, then one could assume that the MOV operated contributing to the line resistance thus causing it to be disproportional to the line reactance found. Then it can be assumed that the MOV did in fact operate and that the capacitor must have been part of the fault loop.

Again, such a method strictly depends on accurate phasor measurement and computation which is extremely difficult to do during the transient period following a fault on a transmission line with an MOV protected series capacitor. Therefore this method was not studied either since it would be very difficult to successfully implement.

The three phase test results, the computer test algorithm, and the EMTP files used are in Appendix C.

Chapter 6 - Conclusions

The completion of this research has led to potential solutions to three of the problems in impedance based capacitor compensated transmission line protection schemes. While these three steps still do not provide for a universally applicable computer algorithm, they are a step in the right direction. Further, these techniques, particularly those dealing with the Fast Fourier Transform (FFT) and its application, may prove helpful in solving other problems unrelated to power system protection.

1) Determination of a method capable of resolving two very closely spaced frequencies from the voltage and current waveform data collected following a fault. This is an important concept for analyzing the subsynchronous frequency which is present in the "post fault domain" (caused by the presence of the capacitor on the line). The capacitor causes the natural frequency of the line to be less than the fundamental frequency of 60Hz. Therefore once the magnitude and frequency of the subsynchronous voltage and current signals is determined, as well as 60Hz synchronous component, then we can determine the L and C of the line as separate quantities.

The solution found was somewhat simple. Taking an FFT of the 4 post fault cycles and fitting a curve to the data points above 60Hz provides a means for determining how much of the 60Hz result was due to the presence of the subsynchronous frequency. Once this is known, the correct 60 Hz value is computed and the frequency spectrum can then be corrected by removing the *actual* 60Hz component. This allows for the construction of an accurate spectrum of the subsynchronous frequency component. An inverse FFT is then used to determine a set of data points in the time domain which reflect the subsynchronous signal. The FFT is then calculated a number of times with varying window lengths until one clear "spike" emerges. This indicates the stopping point. The frequency of this one single spike is the correct frequency of the subsynchronous component of the post fault voltage or current signal. Also, the magnitude of this spike is then an accurate representation of the magnitude of the subsynchronous component.

2) In the case of a single phase to ground fault, the method for calculating the fault impedance is to use the formula:

$$Zfault = \frac{V_{phase}}{I_{phase} + (mI_0)}$$

Where I_0 is the zero sequence current equal to one third of the sum of I_a, I_b, and I_c or:

$$I_0 = 1/3*(I_a + I_b + I_c)$$

And where m is a factor given by:

$$m = \frac{Z_0 - Z_1}{Z_1}$$

This is however the expression describing m in a line that does not include series capacitance. The value of m in that case is independent of distance to the fault. However, when considering a line with series capacitors installed, it can be concluded that the value of m when the capacitor is switched into the line is given by:

$$m = \frac{Z_0 - Z_1}{Z_1 - Z_C}$$

Consequently, the value of m is based on fault location. Since that is unknown in practical situations, it becames necessary to use an iterative type method to find a solution. The algorithm first examines the frequency signature of the appropriate voltages and currents and looks for subsynchronous values which would indicate that the capacitor was switched into the line at the time of fault inception. If it does not find these values, it reverts to the traditional method of determining fault impedance. If a strong subsynchronous value is present, then a guess is made for the value of m and the final determination is made with an iterative approach, thus eliminating this second obstacle.

3) Determination of the MOV's status at the time of the fault is another important piece of the overall solution (i.e. Was the capacitor part of the fault loop?). This is critical since the results of the FFT are polluted when the MOV operates. Therefore, the decision of a relay would be completely incorrect if it believes that the MOV has not operated and depends on the solution presented here for its logic. The MOV causes clipping of the waveforms

when it operates. This clipping is in essence a step change being imposed on the system each time it occurs. It is known that when step changes are imposed upon a system, the result is the presence of the entire frequency spectrum for a short time following the impulse. Consequently, it is possible to determine if the MOV operated (which would imply that the capacitor was part of the fault loop) based on a continued presence of all harmonics during the cycles immediately following the inception of the fault. By examining the post fault spectral results for the presence of 3^{rd} 5^{th} and 7^{th} harmonics measuring a nominal value of 5% of the fundamental, it is possible to suggest conclusively that the MOV operated and thus the capacitor was part of the fault loop. This does not trigger falsely for events such as transformer inrush and overexcitation since the algorithm searches for content of **all** three harmonics in the signal in order to make a decision. It is also noted that the first cycle of post fault data should be omitted from this analysis. This is due to the fact that indications of a step change would also indicate MOV operation. Unfortunately, the initial fault inception is a step change and thus the first cycle of post fault data could fool this method into determining MOV operation took place if the first cycle of post fault data was included in the analysis.

Clearly, further study is necessary to solve the problem of capacitor compensated transmission line protection. When the MOV operates, it renders our most often relied upon tool in computer relaying, the FFT, useless. This particular research has answered some questions which potentially give computer based relays the necessary tools to make accurate relaying decisions in all cases not involving MOV operation, and in some cases where knowing that the MOV operated gives an indication of fault location.

It should be noted that in all test cases where the MOV did not operate, the results found using the methods discussed here were quite good. Estimations of the positive line reactance to the fault were within 90% on all tests regardless of line conditions, fault inception angle, or type of fault.

References

[1] "Overview of Series-Compensated Line Protection Philosophies", Finn Andersson, and Walter A. Elmore, Western Protective Relay Conference October 23-25, 1990, pg. 2-3.

[2] "Power System Relaying", Stanley H. Horowitz and Arun G. Phadke, (book), Second edition, Research Studies Press Ltd., England, 1995, pg. 116,132.

[3] "Computer Relaying for Power Systems", Arun G. Phadke and James S. Thorp, (book), Research Studies Press Ltd., England, 1988, pg. 87, 160.

[4] "Limits to Fault Location Accuracy", Arun G. Phadke, and M. A. Xavier.

[5] "CIGRE Application Guide on Protection of Complex Transmission Network Configurations", E. Bondia, J.L. Carel, P.O. Gjerde, L. Lohage, J. Maas, G. Pratesi, J. Zakonjsek, R.G. Coney, G.G. Correa, D.C. Dawson, M.V. Gonzalez Sabato, and A. Palamarczuk, CIGRE paper SC34-WG04, May 1991, sec. 7.1.1, 7.2.4, 7.3.

[6] "Improvements in Fault Location Estimate", Damir Novosel, Arun G. Phadke, and Walter A. Elmore, pg. 6-7.

[7] "Elements of Power System Analysis", William D. Stevenson Jr., (book), Fourth edition, McGraw-Hill, Inc., New York, 1982, pg. 110-111.

[8] "IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems", Industrial and Commercial Power Systems Committee of the IEEE Industry and Applications Society, (book), ANSI/IEEE Standard 242-1986, Revision of IEEE Std 242-1975, The Institute of Electrical and Electronic Engineers, Inc., New York, 1986, pg. 117-118, 129-132, 134-140.

APPENDIX A

Literature Search

Appendix A - Literature Search

In order to develop a firm background knowledge of distance relaying as it pertains to series compensated transmission lines, as well as to be able to discuss this topic intelligently, there are a number of texts which must be considered. Some of the more well known papers and books on the topic (and other related topics) have been summarized below. These summaries focus on that material which is pertinent to the protective relaying discussion at hand.

(1) "Overview of Series-Compensated Line Protection Philosophies"

Fin Andersson

Walter A. Elmore

This particular paper on series compensated line protection covers a number of important topics in the study of this complex problem. First Andersson and Elmore examine the basic cause of the problems associated with traditional schemes when applied to a capacitor compensated line. The addressed problems include spark gap flashover, MOV operation / transfer of capacitor reactance to resistance by metal oxide element bridging of the capacitor, distortion of the apparent impedance seen at the relay site, voltage reversal (inversion), current reversal (inversion), delayed impedance swing due to low frequency transient component, false voltage "zeros" on adjacent lines which do not have faults, and power reversal (in the case of parallel lines).

The topics of most interest to us are MOV operation (transfer of capacitive reactance to resistance), voltage inversion, and delayed impedance swing due to low frequency. Andersson and Elmore provide a graph which shows the apparent impedance of a single line with a fault at the far end. It displays the different line "shapes" depending on spark gap operation, MOV operation, and no capacitor-protective device operation. This drawing alone sheds some light on the complexities associated with series capacitor compensated line protection schemes. The discussion on voltage reversal indicates the nature of faults which are typically close to the capacitor, but on the opposite side of the capacitor from the relay, appearing as reverse faults to the relay. According to the paper, a large negative reactance is seen if the negative reactance of the series capacitor is greater than the positive reactance of the line section to the fault location. The relay sees that the fault is behind it since a regular transmission system has only series inductive reactance. The negative impedance value would then tend to mean a reverse fault, however here the fault is actually a forward fault clearly in the zone of protection of the relay. This is one of the biggest problems facing a solution to this relaying question.

Next the topic of the “low frequency transient component” is discussed. This transient component is of course the natural frequency of the system which is present after the step impulse caused by the fault. Since there is nothing driving this response, it dies off rather quickly. The paper is concerned with the effect which this has on the speed and trajectory of the impedance change seen by the relay. This slow (100ms) spiral path from pre to post fault impedance can cause many erroneous relaying decisions.

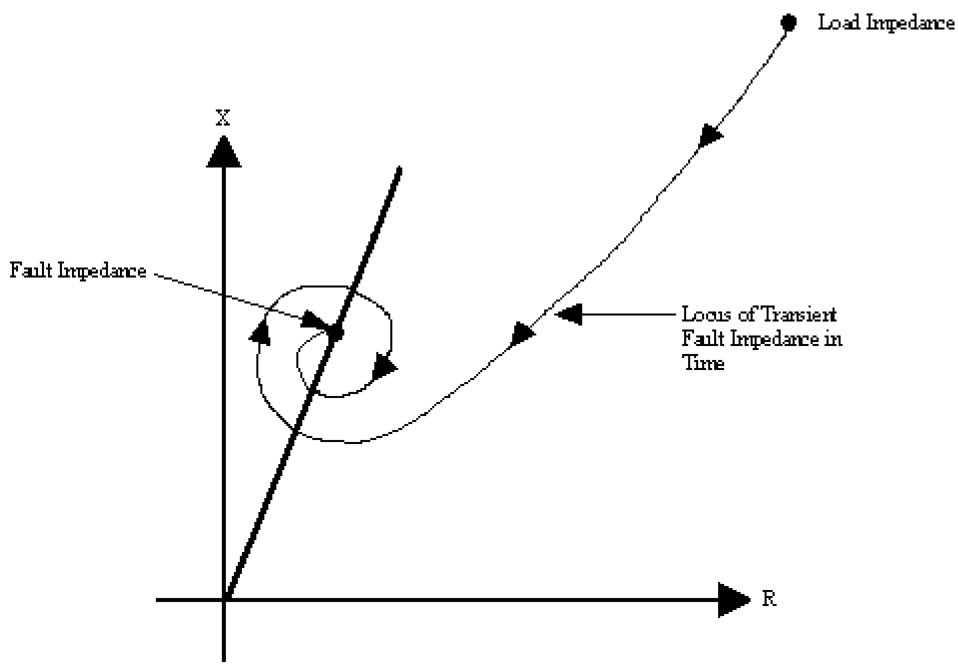


Figure A.1.1 – Impedance Trajectory of a Faulted Line Section of a Series Compensated Transmission Line

Andersson and Elmore suggest using band pass filtering to eliminate two problems. High pass filtering with a very sharp cut off to eliminate the low frequency oscillation, and Low pass filtering to remove high frequency components resulting from gap flashover. The resulting signal should give a good idea of the actual V and I and thus the actual impedance of the line. The only problem with this approach to removing the low frequency is that it requires a filter capable of not interfering with the 60Hz component, however one which blocks everything below

60Hz almost completely. This type of filter is very difficult to produce in practice and would lead to a slow speed of response.

This paper continues on with a number of potential schemes which are based on double ended line protection with some form of communications. The problem with most of these schemes has to do with voltage, current, or power reversal in one way or another. The paper ends up with two important notes. First, the importance of combinations. Obviously when faced with such a complex problem, it is important not to restrict oneself to only one protection scheme. To achieve dependability and security, it is best to have multiple schemes at work in evaluating a line and then to take all results into account before issuing a relaying decision. And finally, there is an important note on Model Power System testing (mostly applicable when a specific system is being considered) as well as EMTP testing.

(2) "Power System Relaying – Second Edition"
Stanley H. Horowitz
Arun G. Phadke

Section 5.10 Effect of Transmission Line Compensation Devices

This section of the text deals briefly with the effects of series capacitors used to increase transmission line load or stability margins, and series reactors which are installed to reduce or limit short circuit currents. The article addresses the effects of these devices on transmission line protection. Our interest in this section is purely in the area of series capacitor compensated lines. Phadke and Horowitz begin with an explanation of the assumptions made in traditional protection schemes which do not apply to lines with series compensation. These are: Fault currents reverse direction only for faults on two sides of a relay, and that the ratio of voltage to current at a relay location is a measure of the distance to a fault. The paper discusses the reason for close in faults appearing to be reverse faults as well as the fault locations which will produce accurate results.

Phadke and Horowitz then address the effects of the series capacitor's own protection on the protection scheme of the actual transmission line. Two possible solutions to the problem are given….first, wait for the protective device on the capacitor to remove it from the line, and then act. Second, phase comparison relaying is suggested as a possible solution.

Section 5.4 Three Phase Distance Relays

This section is of interest as it covers several basic topics pertaining to distance relaying. Since the solution being investigated is based on traditional distance relaying, there is useful information in this section of Phadke and Horowitz's book. There is a brief description of the 10 different fault types which are possible. Then it is noted that all distance relaying schemes are based on determining the impedance to the fault by taking the ratio of voltages and currents in order to determine positive sequence impedance to the fault.

Next, the different fault types are examined using symmetrical components to determine the appropriate quantities to use in finding the correct impedance to the fault. Particularly important here is the discussion on phase to ground faults. There is an explanation of the computation of the compensated phase current which is necessary to determine the impedance to the fault.

(3) "Computer Relaying for Power Systems"
Arun G. Phadke
James S. Thorp

Chapter 3 Mathematical Basis for Protective Relaying Algorithms

This chapter of Phadke and Thorp's book is concerned with the Fourier transform, the fast Fourier transform, and the use of these tools in computer relaying. The chapter begins with a discussion of the Fourier series including periodic functions, fundamental frequency and the general information provided in a Fourier series. The chapter continues to describe the mathematical procedure involved in computing a Fourier transform, the expected results and the limitations of the transform. There is a discussion of the discrete Fourier transform, and the filter like nature of the DFT.

The chapter then discusses the topics of probability, random processes, and Kalman filtering which are not of any particular interest to us.

(4) "Limits to Fault Location Accuracy"
A.G. Phadke
M.A. Xavier

As the title implies, this paper investigates the limits of accuracy on fault location. The paper is concerned with single ended schemes (where data from one end of a faulted line is available). In the first section "Sources of

Errors", the places where errors enter into the computation of fault location are enumerated. These include transducer error (current and potential transformer errors), model errors (faulty model of the line being protected), measurement errors (amplifiers and A/D converter error), and finally algorithm errors. In this case, all four apply and have some significance in the series compensated line relaying problem.

The drive behind the paper is to determine just how close to perfect the results can be in order to have a finishing point to look toward. Knowing this point is essential in order not to take extreme measures to reduce the error to impossible levels.

Transducer error is addressed first. It is quickly written off as an error which cannot be corrected. There fore it sets the "floor" of the error "budget". Model errors are another story. These errors are caused by misconception of the transmission line in the model used to evaluate it. This can be caused by poor information leading to improper incremental impedance determination, omitted information such as charging capacitance or series resistance. The largest error is determined to be in determining the zero sequence impedance of the line. This is potentially troublesome to us as our algorithm uses a "guess" for the value of m to begin with and then iterates. There is already some uncertainty here due to our procedure.

Measurement errors are considered next. The major sources of measurement errors are missing information and flaws in measurement due to gain errors, non-linearity, dc offsets and A/D errors. All of these are potential problems and therefore this text is important to us. Finally, algorithm errors are addressed. These errors cover line items such as numerical instability in algorithms to poor choice of approaches. Again, all pertinent to the discussion at hand.

Following this discussion, a series of algorithms are developed and discussed. These are based in part on the Takagi algorithm and include fault location with load current compensation, a formula which does not require source impedances, correction algorithm for untransposed lines as well as some numerical examples. There is then a discussion on implementation issues and a conclusion which summarizes the entire paper.

(5) "CIGRE – Application Guide on Protection of Complex Transmission Network Configurations"

E. Bondia	J.L. Carel	P.O. Gjerde
L. Lohage	J. Maas	G. Pratesi
J. Zakonjsek	R.G. Coney	G.G. Correa
D.C. Dawson	M.V. Gonzalez Sabato	A. Palamarczuk

Chapter 7 Protection of Series Compensated Lines

This document is a very thorough summary of series compensation and the available protection configurations that will give adequate protection for the delicate and expensive series capacitor. There is an early discussion of the merits of series compensation, and the merits of certain locations for placing the series capacitor on a line.

There is a discussion of the maladies which the transmission line and its protection scheme face when series compensation is added to a line. These are the same problems sited in other documents. Namely, impedance variations depending on spark gap and MOV operation, voltage and current inversion, subsynchronous oscillations, slow increase in short circuit current due to subsynchronous transient component. They also covered two problems not previously mentioned. These problems are negative lumped reactance connected in series with distributed positive reactance, dissymmetries due to non-symmetric gap flashover and reinsertion and amplification of the existing dissymmetries of non-transposed lines causing circulating negative sequence currents.

There is a presentation of the apparent impedance for a line compensated at 50% of its length, and one for a line compensated at the very beginning of the line. This is followed by voltage and current inversion discussions quite similar to those in the Andersson and Elmore paper discussed previously. Here, the authors have mentioned the famous problem of subsynchronous resonance which is clearly aggravated by the presence of series compensation. They have addressed the problems that this phenomenon can cause for generator shafts.

Finally their discussion on the protection of series capacitors themselves begins. There is an explanation of air gap protected capacitors which is interesting and informative however not directly related to our interests. Next, the paper turns towards our topics of interest with a discussion of MOV protection. It is explained that the MOV in many cases is used in parallel with a spark gap and a circuit breaker. The MOV operates first, then the spark gap, and finally, the circuit breaker closes and shorts around the capacitor to save it from damage.

This document is somewhat dated since newer installations on high voltage transmission lines do not make use of the spark gap. For this reason the scope of our investigation covers only capacitors with MOV and circuit breaker parallel protection.

Again, we see that the problem of subsynchronous resonance is addressed. Here a more in depth discussion of the interaction between electrical and mechanical natural frequencies is discussed. When these natural frequencies are very close, severe damage to the generator shaft can take place when subsynchronous oscillations grow slowly without being noticed. In some rare instances this damage has been catastrophic. This problem can be eliminated by use of a suitable exciter control system.

This document contains the first discussion of placement of instrument transformers that we have come across thus far. The distinct advantages of line side and bus side placement of CVT's and PT's are discussed and compared. The disadvantages of each are also addressed, and it is pointed out for the purposes of non-communications based systems that bus side protection offers the advantage of making the capacitor part of the transmission line. Consequently, if there is a fault in the capacitor or one of its shunt devices, the line protection will trip thus protecting the capacitor.

The CIGRE guide next addresses the issues pertinent to the protection of the actual transmission line on which the capacitor has been installed. First, underreaching and overreaching schemes are examined. The author specifies that permissive overreach mode is the most commonly used. Underreaching schemes cannot be depended upon to provide adequate primary protection since the capacitor's own protection (removing or shorting the capacitor) will cause there to be a section of the line for which there is no instantaneous tripping at all. So, there are several solutions and alternatives which are discussed. Several relay characteristics are presented and their advantages and disadvantages enumerated. A discussion of double circuit series compensated lines follows beginning with the mention of a troubling problem for all parallel lines, mutual impedance in the zero sequence. This problem is aggravated on lines with series compensation.

Again, the phenomenon of current reversal on parallel lines is visited. The problem of current changing direction in the healthy line when only one of the two end breakers has tripped on the faulted line. Directional comparison and other communication based protection schemes are discussed following this, however that is again not part of our scope of interest.

Following this section there is a collection of statistical data on series capacitor installations in use around the world. While interesting information, it does not have significance to our work and therefore will not be considered.

Section 7.12 is entitled "Transients on Series Compensated Lines". Here a derivation is given for the natural frequency of a series RLC system. This expression assumes a significant series R and an insignificant shunt C or charging capacitance. This is slightly different from the premise which our solution is based on. We have assumed that both parameters are insignificant in order to simplify to two equations and two unknowns. The results prove that this was a reasonable assumption.

(6) "Improvements in Fault Location Estimate"
Damir Novosel
Arun G. Phadke
Walter A. Elmore

This paper contains an investigation of a new technique for estimating fault location which only requires that data be supplied from one end of the line. The technique compensates for fault resistance, load flow, and is insensitive to the zero sequence current distribution factor. Clearly a major advantage to this type of algorithm is that communications are not required. However, to eliminate or significantly reduce the error introduced by fault resistance, it is necessary to have knowledge of the system source impedance. Their approach has made certain assumptions in order to reduce the dependence on knowing source impedance.

A listing of the factors which play a part in error of the locator algorithm follow. Line model inaccuracies, uncertain knowledge of the line parameters, influence of the mutual effects on the zero sequence components, measurement errors, load flow, presence of shunt reactors, shunt and series capacitors, and tapped lines, all play a role in degrading fault location estimates.

One approach to eliminating the error introduced by uncertain fault resistance is to analyze only the imaginary part of the apparent line impedance. Then the real quantity R is not of importance and does not have bearing on the solution to the problem. Next, a discussion of the algorithms which do and do not require source impedance information is presented. The Takagi method is considered and analyzed in the discussion on algorithms which do require source impedances.

The paper recommends a non-iterative approach which does not make use of source impedances. It assumes that the negative sequence distribution factor is a real number. What follows is a mathematical analysis of the algorithm as it applies to single phase to ground faults, phase to phase to ground faults, phase to phase faults, and three phase faults. Upon analysis of this algorithm, several conclusions are drawn. The algorithm does not exhibit any error if negative sequence current distribution factor is in fact a real number. This approach accounts for pre-fault load flow quite well, and a good level of accuracy is predicted for most common fault types. An even better estimate can be reached if the algorithm is adjusted to compensate for charging capacitance, shunt elements, and untransposed lines. The technique is also applicable to radial lines.

(7) "Elements of Power System Analysis"
William D. Stevenson, Jr.

Section 5.9 Reactive Compensation of Transmission Lines

Stevenson briefly addresses inductive and capacitive compensation of transmission lines. The text points out the performance problems which are observed on medium to long transmission lines. Namely, these problems consist of significant voltage drop over the length of the line, and the maximum power transfer limit which is determined by the series impedance of the line. There is a discussion of analysis of series compensated lines using ABCD constants. When the conditions of different points on the line are not of concern, (i.e. only the conditions at the ends are of interest) the series combination may be considered as a whole with a single set of parameters. When conditions on the line are of interest, then ABCD constants must be determined for the segments on each side of the capacitor as well as for the capacitor itself. Then the total line is represented by the sum of the three models.

Stevenson then lists some of the more beneficial uses for series capacitors. In the southwest portion of the United States where generating plants can be hundreds of miles from their load, the increased power transfer capability and the lower voltage drop in series compensated lines can be a real benefit. Further, series compensation can be helpful in balancing the voltage drop of two parallel transmission lines.

(8) "IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems" – The IEEE Buff Book
Industrial and Commercial Power Systems Committee
of the
IEEE Industry Applications Society

Section 3.1.4 Accuracy [of Current Transformers]

The key elements of current transformer inaccuracy are quickly discussed in this section. The main problem with current transformers is the threat of saturation during particularly high current faults. Accuracy of the current transformer at high overcurrents depends on two major characteristics of the design of CT. These two characteristics are the area of the cross section of the core, and the number of windings in the secondary of the CT. The greater the area of the cross section of the core, the more flux can be developed before "saturation" occurs moving the CT into an operating region of excessive inaccuracy. Along those same lines, the more windings there are in the secondary of the CT, the lower the flux needed to "force" the secondary current through the burden (the relay).

Section 4.3 Distance Relay – Device No. 21

This section gives a brief description of distance relays from a selection perspective. The distance relay is a family of relays which are ohmic, meaning that they react to the various impedance characteristics of the line which they are protecting. The reactance type relay looks only at the reactive component of the line impedance. Its characteristic is a straight line parallel to the R axis. This is a benefit in that fault arc resistance has almost no effect on the predicted operation of the device. The problem is that reactance type relays can sometimes operate for load currents.

An impedance relay makes use of the real and imaginary parts of impedance to the fault. The characteristic is a circle centered at the origin with radius equal to $(R_1^2+X_1^2)^{1/2}$. The relay setting is $Z=R_1 + jX_1$. The impedance relay still has the problem of non directionality. To solve this issue, the impedance relay should be used with other relays to effectively restrict its reach in the reverse direction (third quadrant of the R-X diagram).

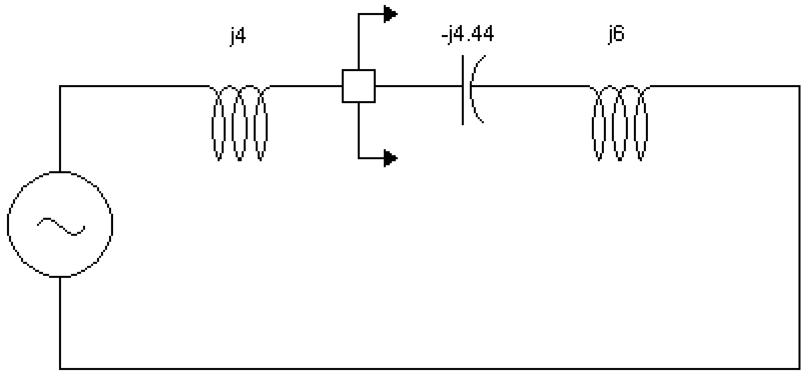
The MHO type distance relay measures complex admittance, and has the added advantage of being directional. The MHO characteristic is circular like the impedance relay, however the circle lies mostly in the first quadrant of the R-X diagram. The MHO characteristic can be shifted for either forward or reverse directionality in certain circumstances.

Finally, this brief but informative section describes a hybrid MHO supervised reactance relay which places the operation contacts of the MHO and the reactance relays in series so that the combination only "acts" for faults which are in the overlapping portion of their characteristics.

APPENDIX B

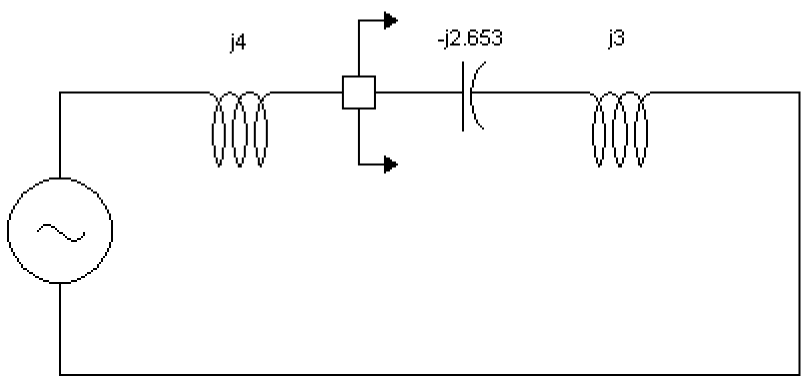
Tests of Algorithm with Simple Single Phase Model

Test #1 – Resonance of 40Hz as a Test



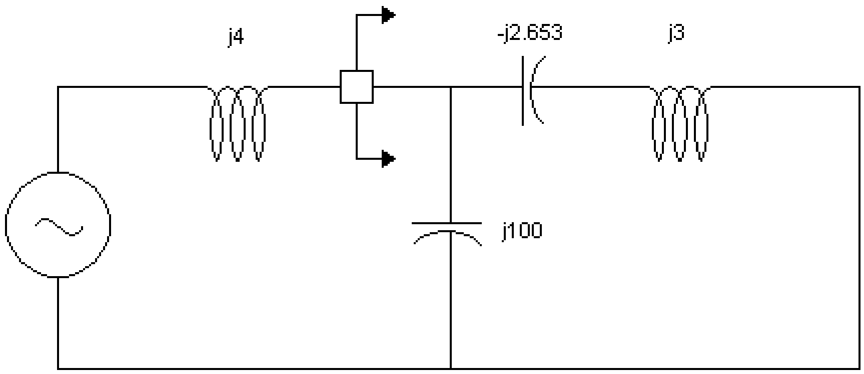
Results: X_C 4.452 X_L 6.018

Test #2 – Random Resonance Frequency (36.9Hz)



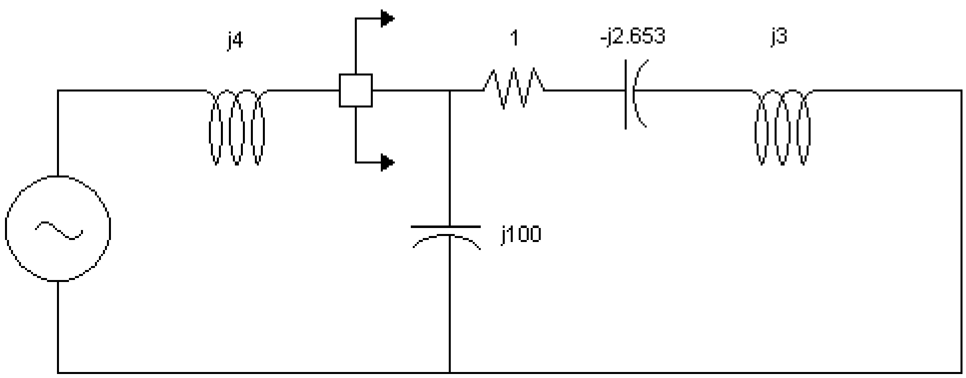
Results: X_C 2.738 X_L 3.093

Test #3 – Random Resonance Frequency with Added Shunt C



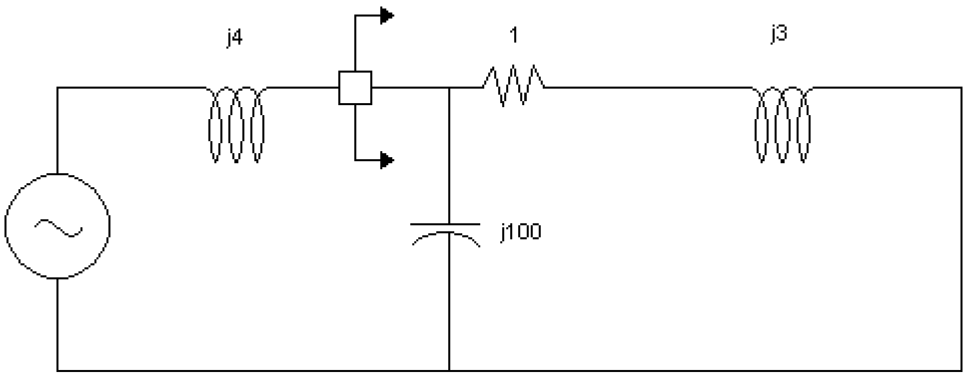
Results:	$\mathbf{X_C}$	$\mathbf{X_L}$
	2.709	3.064

Test #4 – Random Resonance Frequency with Added Shunt C and Series R



Results:	$\mathbf{X_C}$	$\mathbf{X_L}$
	2.963	3.310

Test #5 – Random Resonance Frequency with Shunt C and Series R with No Series C



Results:	**X_C**	**X_L**
	0.004	3.003

APPENDIX C

3 Phase Results
3 Phase Sample Algorithm
3 Phase Sample EMTP Test File

Fault Type	Rev. Fault L (-15Ω)	Rev. Fault C (0Ω)	50% Fault L (60.5Ω)	50% Fault C (64Ω)	112% Fault L (136Ω)	112% Fault C (64Ω)	50% Fault No Cap L (60.5Ω)	50% Fault No Cap C (0Ω)
a-g	-15.14	0.00	63.80	64.00	136.32	64.00	60.58	0.00
b-g	-15.15	0.00	63.79	64.00	136.33	64.00	60.58	0.00
c-g	-15.15	0.00	63.81	64.00	136.32	64.00	60.58	0.00
a-b	-15.14	0.00	60.67	64.00	136.31	64.00	60.53	0.00
b-c	-15.14	0.00	60.58	64.00	136.36	64.00	60.52	0.00
c-a	-15.14	0.00	60.73	64.00	136.33	64.00	60.53	0.00
a-b-g	-15.15	0.00	60.78	64.00	136.32	64.00	60.59	0.00
b-c-g	-15.14	0.00	60.71	64.00	136.36	64.00	60.58	0.00
c-a-g	-15.14	0.00	60.65	64.00	136.32	64.00	60.59	0.00
a-b-c	-15.14	0.00	60.68	64.00	136.36	64.00	60.50	0.00

Table of results from 3∅ tests where capacitance values above a set level were assumed to be 100% of the installed capacitance (64Ω), fault inception at Voltage Maximum

Fault Type	Rev. Fault L (-15Ω)	Rev. Fault C (0Ω)	50% Fault L (60.5Ω)	50% Fault C (64Ω)	112% Fault L (136Ω)	112% Fault C (64Ω)	50% Fault No Cap L (60.5Ω)	50% Fault No Cap C (0Ω)
a-g	-15.14	0.00	61.92	64.00	136.29	64.00	60.52	0.00
b-g	-15.14	0.00	62.04	64.00	136.27	64.00	60.53	0.00
c-g	-15.13	0.00	62.13	64.00	136.28	64.00	60.53	0.00
a-b	-15.14	0.00	60.85	64.00	136.31	64.00	60.48	0.00
b-c	-15.14	0.00	60.75	64.00	136.26	64.00	60.49	0.00
c-a	-15.14	0.00	60.71	64.00	136.30	64.00	60.55	0.00
a-b-g	-15.15	0.00	60.74	64.00	136.25	64.00	60.59	0.00
b-c-g	-15.13	0.00	60.78	64.00	136.27	64.00	60.58	0.00
c-a-g	-15.12	0.00	60.60	64.00	136.31	64.00	60.59	0.00
a-b-c	-15.14	0.00	60.59	64.00	136.33	64.00	60.48	0.00

Table of results from 3∅ tests where capacitance values above a set level were assumed to be 100% of the installed capacitance (64Ω), fault inception at Voltage Minimum

```
%%%% Algorithm for Finding Series L and C of Transmission %%%%
%%%%            Line Using Post Fault Data          %%%%
%%%%                    Written as MATLAB ".m" File          %%%%


clear
% Input Fault Type
% Types are  1=ag 2=bg 3=cg 4=ab 5=bc 6=ca 7=abg
%             8=bcg 9=cag 10=abc

FT=1;

% Input Z0,Z1,and ZC all in ohms

Z0=(117+j*363);
Z1=(5+j*120.8);
ZC1=-j*64;

% Input Data

x=wk1read('c:\student\_clint\old_cl~1\nomovag');

ee=512;
x=x(129:ee,:);
nu=length(x);
time=(x(5,1)-x(4,1));

Ia=x(:,3);                      Va=x(:,2);
Ib=x(:,5);                      Vb=x(:,4);
Ic=x(:,7);          Vc=x(:,6);


testp=fft(Ia);
testp=abs(testp);
num=length(testp);
f=(1/(time)*((0:num-1)/num));
% subplot(2,1,1)
stem(f,(testp*2/nu),'k');
title('FFT of current signal for A to G Fault...with MOV operation')
xlabel('Frequency (Hz)')
ylabel('Magnitude')
axis([0 1000 0 8000])


if FT==1
        V=Va;   I=Ia;     I0=(1/3)*(Ia+Ib+Ic);
elseif FT==2
        V=Vb;   I=Ib;     I0=(1/3)*(Ia+Ib+Ic);
elseif FT==3
        V=Vc;   I=Ic;     I0=(1/3)*(Ia+Ib+Ic);
elseif FT==4 | FT==7
        V=Vb-Va;          I=Ib-Ia;
elseif FT==5 | FT==8
        V=Vc-Vb;          I=Ic-Ib;
elseif FT==6 | FT==9
        V=Va-Vc;          I=Ia-Ic;
elseif FT==10
        V=Vb;   I=Ib;
end
```

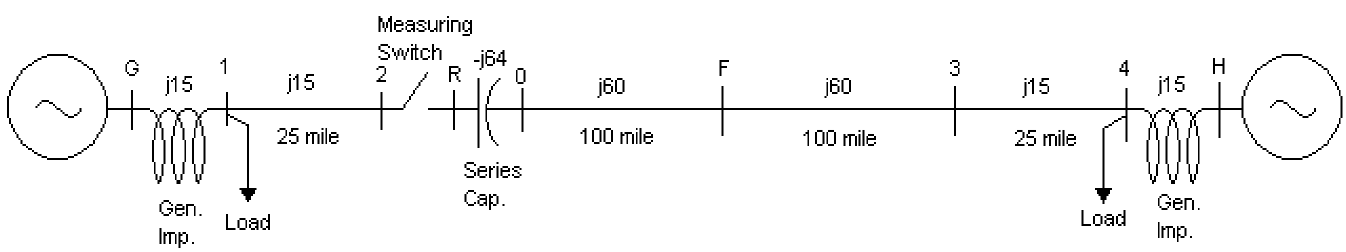
```
  X=fft(I);

%% seperates real and imaginary components of test data in the vacinity of the
%% 60Hz fundamental and the frequencies below

XREAL=real(X);
XREAL=[XREAL(8),XREAL(9),XREAL(10),XREAL(11),XREAL(12),XREAL(13),XREAL(14),XREAL(15)];
XIMAG=imag(X);
XIMAG=[XIMAG(8),XIMAG(9),XIMAG(10),XIMAG(11),XIMAG(12),XIMAG(13),XIMAG(14),XIMAG(15)];

%% basis for frequency values associated with the different magnitudes present
%% in the fft generated spectrum

f=(1/time)*(0:nu-1)/nu;

%% caclculates a 6th order polynomial fit to determine the actual Real and
%% Imaginary 60Hz components in order to accurately calculate the true 60Hz
%% uncorrupted magnitude

g=[f(8),f(9),f(10),f(11),f(12),f(13),f(14),f(15)];

p=polyfit(g,XREAL,6);
q=polyfit(g,XIMAG,6);

fitp=polyval(p,60);
fitq=polyval(q,60);

%% mag, mag1, and mag2 are variables showing the true 60Hz component in complex
%% notation, as a magnitude, and as an angle

mag=(X(7)-(fitp+(i*fitq)))*(2/nu);
X(7)=(fitp+(i*fitq));

Imag=mag;

%% the fft is once again run on the sample test data however, this time the 60Hz
%% component is removed so that the subsynchronous frequencies are the largest
%% present in the signal

xnew=ifft(X);

signal=xnew;
nu=length(signal);
for xxx=1:200;              % xxx is max number of points to "shave off"
        s=nu-(xxx-1);
        FFTS=(2/s)*abs(fft(signal(1:s)));
        [M(xxx),n(xxx)]=max(FFTS(2:6)); %Note: the challenge is right here...How many
                                                %points can be removed from the interval and still
                                        %maintain the 6th value in the fft below say
                                                %57Hz.
        S(xxx)=FFTS(n(xxx)+2);
end

[maxr,m]=max(M./S);

%%m=85;   %%For forcing a run to stop at some preselected window length.

magnitude=M(m);
f=(1/time)*(0:(384-m)-1)/(384-m);
fval=f(n(m)+1);

FA=fval;
```

```
  WA=2*pi*FA;

if FA>57;
        error('no cap present');
end

BLA=(2/(nu-m))*fft(signal(1:(nu-m)));
CURRENT=BLA(n(m)+1);

X=fft(V);

%% seperates real and imaginary components of test data in the vacinity of the
%% 60Hz fundamental and the frequencies below

XREAL=real(X);
XREAL=[XREAL(8),XREAL(9),XREAL(10),XREAL(11),XREAL(12),XREAL(13),XREAL(14),XREAL(15)];
XIMAG=imag(X);
XIMAG=[XIMAG(8),XIMAG(9),XIMAG(10),XIMAG(11),XIMAG(12),XIMAG(13),XIMAG(14),XIMAG(15)];

%% basis for frequency values associated with the different magnitudes present
%% in the fft generated spectrum

f=(1/time)*(0:nu-1)/nu;

%% caclculates a 6th order polynomial fit to determine the actual Real and
%% Imaginary 60Hz components in order to accurately calculate the true 60Hz
%% uncorrupted magnitude

g=[f(8),f(9),f(10),f(11),f(12),f(13),f(14),f(15)];

p=polyfit(g,XREAL,6);
q=polyfit(g,XIMAG,6);

fitp=polyval(p,60);
fitq=polyval(q,60);

%% mag, mag1, and mag2 are variables showing the true 60Hz component in complex
%% notation, as a magnitude, and as an angle

mag=(X(7)-(fitp+(i*fitq)))*(2/nu);
X(7)=(fitp+(i*fitq));

Vmag=mag;

%% the fft is once again run on the sample test data however, this time the 60Hz
%% component is removed so that the subsynchronous frequencies are the largest
%% present in the signal

xnew=ifft(X);

signal=xnew;

FFTS=(2/(nu-m))*(fft(signal(1:(nu-m))));
VOLTAGE=FFTS(n(m)+1);

if FT==1 | FT==2 | FT==3
        X=fft(I0);

        XREAL=real(X);
        XREAL=[XREAL(8),XREAL(9),XREAL(10),XREAL(11),XREAL(12),XREAL(13),XREAL(14),XREAL(15)];
        XIMAG=imag(X);
        XIMAG=[XIMAG(8),XIMAG(9),XIMAG(10),XIMAG(11),XIMAG(12),XIMAG(13),XIMAG(14),XIMAG(15)];
```

```
    f=(1/time)*(0:nu-1)/nu;

    g=[f(8),f(9),f(10),f(11),f(12),f(13),f(14),f(15)];

    p=polyfit(g,XREAL,6);
    q=polyfit(g,XIMAG,6);

    fitp=polyval(p,60);
    fitq=polyval(q,60);

    mag=(X(7)-(fitp+(i*fitq)))*(2/nu);
    X(7)=(fitp+(i*fitq));

    GNDCU=mag;

    xnew=ifft(X);

    signal=xnew;

    FFTS=(2/(nu-m))*(fft(signal(1:(nu-m))));
    GNDC=FFTS(n(m)+1);

    M=(Z0-Z1)/(Z1+ZC1);

    Z0S=real(Z0)+j*((imag(Z0)/60)*FA);
    Z1S=real(Z1)+j*((imag(Z1)/60)*FA);
    ZC1S=(ZC1/FA)*60;
    MSUB=(Z0S-Z1S)/(Z1S+ZC1S);

    XA=VOLTAGE./(CURRENT+MSUB*GNDC);
    XA=imag(XA);
    XB=Vmag/(Imag+M*GNDCU);
    XB=imag(XB);
else
    XA=VOLTAGE./CURRENT;
    XA=imag(XA);
    XB=Vmag/Imag;
    XB=imag(XB);
end

WB=2*pi*60;

C=((-WB^2+WA^2)/(WA^2*WB^2))/((XA/WA)-(XB/WB));
L=(XA*WA-XB*WB)/(WA^2-WB^2);

Xc=1/(2*pi*60*C);
Xl=2*pi*60*L;

if FT==4 | FT==5 | FT==6 | FT==7 | FT==8 | FT==9 | FT==10
    tol=.3*abs(ZC1);
    if (Xc<=(abs(ZC1)+tol)) & (Xc>=(abs(ZC1)-tol))
        Xc=abs(ZC1)
        Xl=XB+Xc
    else
        Xc=0
        Xl=XB
        if Xl<0
            'WARNING:  REVERSE FAULT'
        end
    end
else
```

```
   'Phase to Ground Fault'
   tol=.9*abs(ZC1);
  if (Xc<=(abs(ZC1)+tol)) & (Xc>=(abs(ZC1)-tol))
        Xc=abs(ZC1)
        Xl=XB+Xc;
        diffy=10;
        while diffy>.2
              percent=Xl/(imag(Z1));
              Z1P=Z1*percent;
              Z0P=Z0*percent;
              Z1SP=Z1S*percent;
              Z0SP=Z0S*percent;
              M=(Z0P-Z1P)/(Z1P+ZC1);
              MSUB=(Z0SP-Z1SP)/(Z1SP+ZC1S);
              XB=Vmag/(Imag+M*GNDCU);
              XB=imag(XB);
              diffy=abs(Xl-(XB+Xc));
              Xl=XB+Xc
        end
  else
        Xc=0
        MM=(Z0-Z1)/Z1;
        Xl=imag(Vmag/(Imag+MM*GNDCU))
        if Xl<0
              'WARNING:  REVERSE FAULT'
        end
  end
end
```

EMTP Test Circuit



Note: EMTP input file on next page.

```
  C Test of Transmission Line with Series Compensation Capacitors
C
BEGIN NEW DATA CASE
C sampling rate of 64 samples a cycle, or 3840/sec @ 60 Hz
C ----dt<---Tmax<---Xopt<---Copt<-Epsiln<-Tolmat<-Tstart
2.604E-4  0.1666     60.
C -Iprnt<--Iplot<-Idoubl<-Kssout<-Maxout<---Ipun<-Memsav<---Icat<-Nenerg<-Iprsup
     01       1       0       1       1                     1
C
C Circuit data....................................
C Bus-->Bus--><----------><----R<----------L<----R<----------<----R<----------
C
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C<----R<----L<----C<----R<----L<----C
C 25 MILE SECTION OF LINE AT GEN 1
 1BUS1A BUS2A              5.3 25.25958E-6
 2BUS1B BUS2B             4.68 10.13-27E-5   5.3 25.25958E-6
 3BUS1C BUS2C             4.68 10.13-27E-5  4.68 10.13-27E-5   5.3 25.25958E-6
C 25 MILE SECTION OF LINE AT GEN 2
 1BUS3A BUS4A              5.3 25.25958E-6
 2BUS3B BUS4B             4.68 10.13-27E-5   5.3 25.25958E-6
 3BUS3C BUS4C             4.68 10.13-27E-5  4.68 10.13-27E-5   5.3 25.25958E-6
C 100 MILE SECTION OF LINE BEFORE FAULT SWITCH
 1BUS0A BUSFA             21.2  101.383E-5
 2BUS0B BUSFB            18.72 40.52-11E-4  21.2  101.383E-5
 3BUS0C BUSFC            18.72 40.52-11E-4 18.72 40.52-11E-4  21.2  101.383E-5
C 100 MILE SECTION OF LINE AFTER FAULT SWITCH
 1BUSFA BUS3A             21.2  101.383E-5
 2BUSFB BUS3B            18.72 40.52-11E-4  21.2  101.383E-5
 3BUSFC BUS3C            18.72 40.52-11E-4 18.72 40.52-11E-4  21.2  101.383E-5
C SERIES CAPACITORS
  BUSRA BUS0A             .001       42.0                            1
  BUSRB BUS0B             .001       42.0                            1
  BUSRC BUS0C             .001       42.0                            1
C GENERATOR 1 INTERNAL IMPEDANCE
 1BUSGA BUS1A              2.51 17.09    0.
 2BUSGB BUS1B             -.849 3.667    0.  2.51 17.09    0.
 3BUSGC BUS1C             -.849 3.667    0. -.849 3.667    0.  2.51 17.09    0.
C GENERATOR 1 INTERNAL IMPEDANCE
 1BUS4A BUSHA              2.51 17.09    0.
 2BUS4B BUSHB             -.849 3.667    0.  2.51 17.09    0.
 3BUS4C BUSHC             -.849 3.667    0. -.849 3.667    0.  2.51 17.09    0.
C LOAD IMPEDANCES
  BUS4A             800.  600.                            1
  BUS4B             800.  600.                            1
  BUS4C             800.  600.                            1
  BUS1A             800.  600.                            1
  BUS1B             800.  600.                            1
  BUS1C             800.  600.                            1
BLANK End of circuit data
C
C .............Switch Data
C
C <-Bus1<-Bus2<---Tclose<----Topen<-------Ie<----Flash<--Request<-----Target<--O
C  SWITCH FOR A B C TO G FAULT
  BUSFA          33e-3       1.
C  BUSFB          33e-3       1.
C  BUSFC          33e-3       1.
C  SWITCHES FOR MEASURING
  BUS2A BUSRA                                MEASURING
  BUS2B BUSRB                                MEASURING
  BUS2C BUSRC                                MEASURING
```

```
  BLANK END OF SWITCH DATA
  C
C Source Data
C <--Bus<I<-----Ampl<-----Freq<----Phase<-------A1<------T1><---Tstart<----Tstop
14BUSGA     462000.0      60.       0.       0.              -1.     9999.
14BUSGB     462000.0      60.      120       0.              -1.     9999.
14BUSGC     462000.0      60.      240       0.              -1.     9999.
14BUSHA     400218.3      60.      -10       0.              -1.     9999.
14BUSHB     400218.3      60.      110       0.              -1.     9999.
14BUSHC     400218.3      60.      230       0.              -1.     9999.
C ..^....1....^....2....^....3....^....4....^....5....^....6....^....^....^....^
C .....^.^.........^.........^.........^.........^........^..........^.........^
BLANK END OF SOURCE DATA
C
C ...........Output Request Data
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
 1
C .....^.....^.....^.....^.....^.....^.....^.....^.....^.....^.....^.....^.....^
C BLANK END OF OUTPUT REQUEST
C
C Plot request Data
C  ______Graph type:  4(volts) 8(branch volts) 9(currents)
C | _____Units: 1(deg)  2(cyc) 3(sec) 4(msec) 5(microsec)
C ||   _________Units per inch
C ||  |    _____Plot starting time
C ||  |   |   _Plot stopping time
C ||  |   |   |     _____Value at bottom of vertical axis (optional)
C ||  |   |   |    |   _Value at top of vertical axis (optional)
C VV<-|<--|<--|<---|<--|Bus-->Bus-->Bus-->Bus-->Heading-------->Vert axis------>
C 2Energize 15mi 1phase Dist NoLoad IdealSrc
C 1442.5 0.0 25.-500.500.BUS2A BUS2B BUS2C       SLGbus2        Bus2 KV
BLANK End of Plot Request
BLANK END OF ALL CASES
```

APPENDIX D

Test of Algorithm to Detect MOV Operation

Test of Algorithm to Detect MOV Operation

When the MOV operates it has a "clipping" or nonlinear effect on the current waveforms. This nonlinear effect is similar to switching or other "step" changes and tends to cause a significant increase in the magnitude of the odd numbered harmonics. Theoretically, all odd harmonics should show increases in their magnitude, however due to the strong inductive nature of the power system, the higher frequency harmonics tend to be choked and are not seen by the relay. Therefore, the strategy used to detect the operation of the MOV (and thus the presence of the capacitor in the fault loop), is to look for the 3rd, 5th, 7th, and 9th harmonics. Setting an arbitrary threshold of 5% of the fundamental, the logic must see this magnitude in each of these four harmonics in order to make the decision that the MOV has operated and subsequently that the capacitor was part of the fault loop. Looking for a combined presence of all of these values guarantees that phenomenon such as transformer overexcitation do not cause the algorithm to trigger erroneously. It could be hypothesized that an evolving fault, due to its transient nature, could fool such an algorithm, however careful selection of the decision tolerance (5% was chosen experimentally) allows for proper responses even in these cases. An evolving fault may only cause 2 or 3 "step" changes in the fault circuit topology thus leading to relatively low odd harmonic content. However, when the MOV goes into a conducting state, it "switches" on or off 4 times per cycle. This continuous change in the fault circuit causes much higher levels of odd harmonics causing the frequency signature of the MOV operation to look quite different than that of an evolving fault. This particular approach was tested on 14 different faults, two of which were evolving faults. The results of these tests are as shown in the following chart. Some waveforms and FFT results are also shown.

MOV Operation?	Fault Type / Evolving Fault?	Fault Inception Angle	Average Percentage of 3rd, 5th, 7th, and 9th Harmonics	Conclusion of Algorithm
No	a-b-c-g	0°	0.7%	No Operation
Yes	a-b-c-g	0°	27.9%	Operation
No	a-b-c-g	90°	0.3%	No Operation
Yes	a-b-c-g	90°	28.6%	Operation
No	a-g	0°	0.5%	No Operation
Yes	a-g	0°	21.4%	Operation
No	a-g	90°	0.2%	No Operation
Yes	a-g	90°	21.7%	Operation
No	b-c	0°	0.3%	No Operation
Yes	b-c	0°	24.42%	Operation
No	b-c	90°	0.7%	No Operation
Yes	b-c	90°	23.7%	Operation
No	a-g…a-b-c-g (evolving fault)	0°	1.5%	No Operation
No	b-g…a-b-g…a-b-c-g (evolving fault)	0°	0.3%	No Operation

It is clear to see from the above summary of the test results, that there is a clear difference in the harmonic content of post fault waveforms when the circuit contains an MOV which has gone into conduction. This clear difference is not even close to being obscured by an evolving fault through the window of consideration. The following section displays some graphs to help the reader visualize these results in both the time and frequency domains.

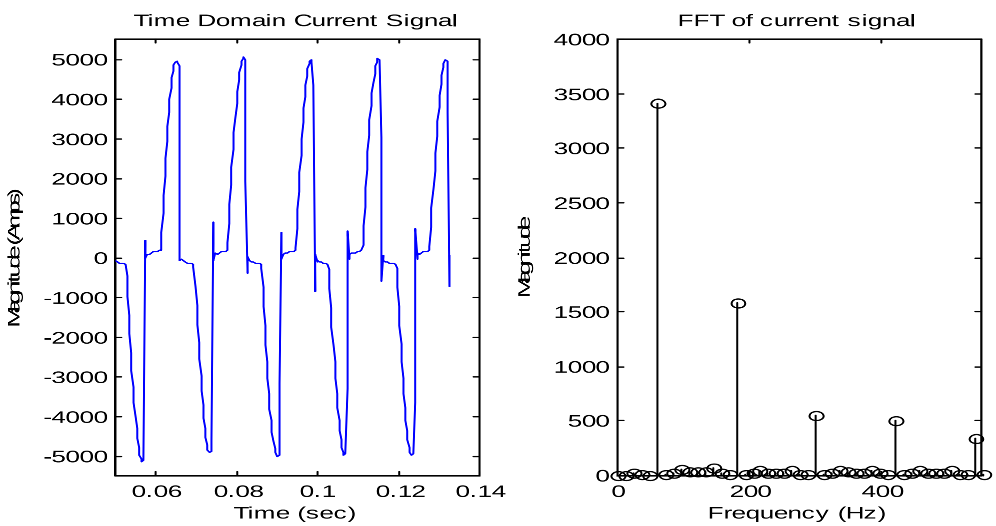


Figure D.1 – Phase to Ground Fault with MOV Operation

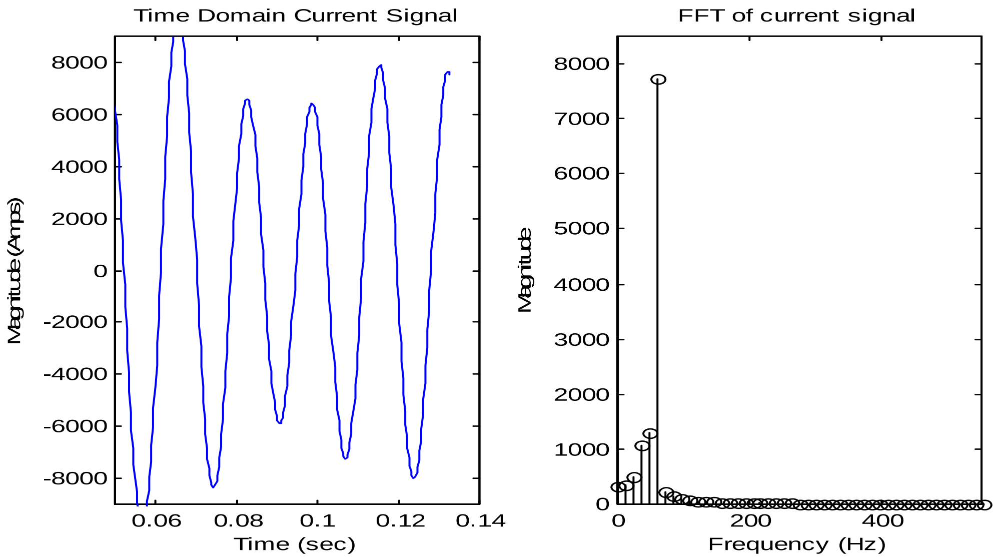


Figure D.2 – Phase to Ground Fault with no MOV Operation

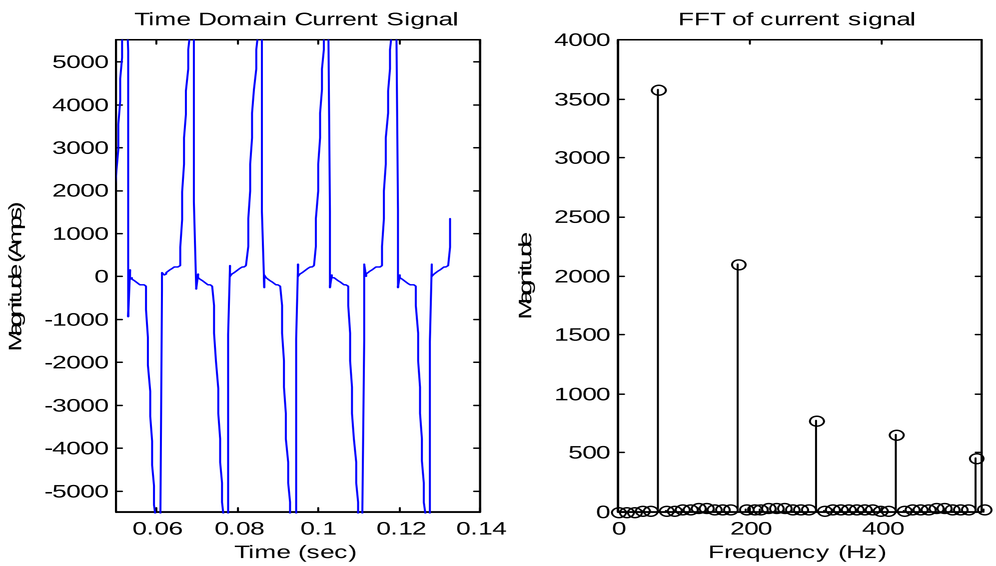


Figure D.3 – Three Phase Fault with MOV Operation

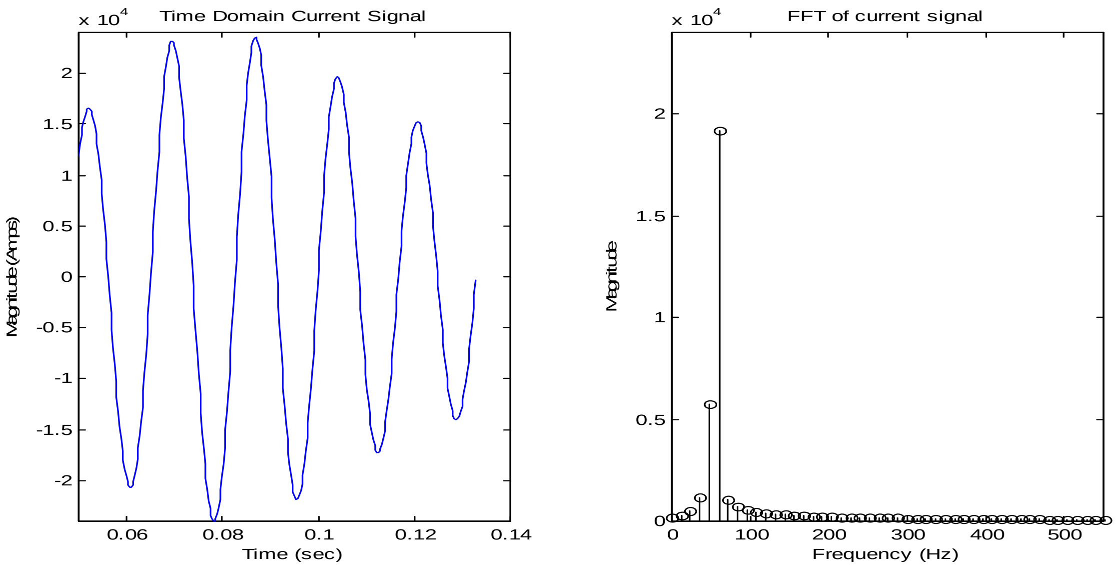


Figure D.4 – Three Phase Fault with no MOV Operation

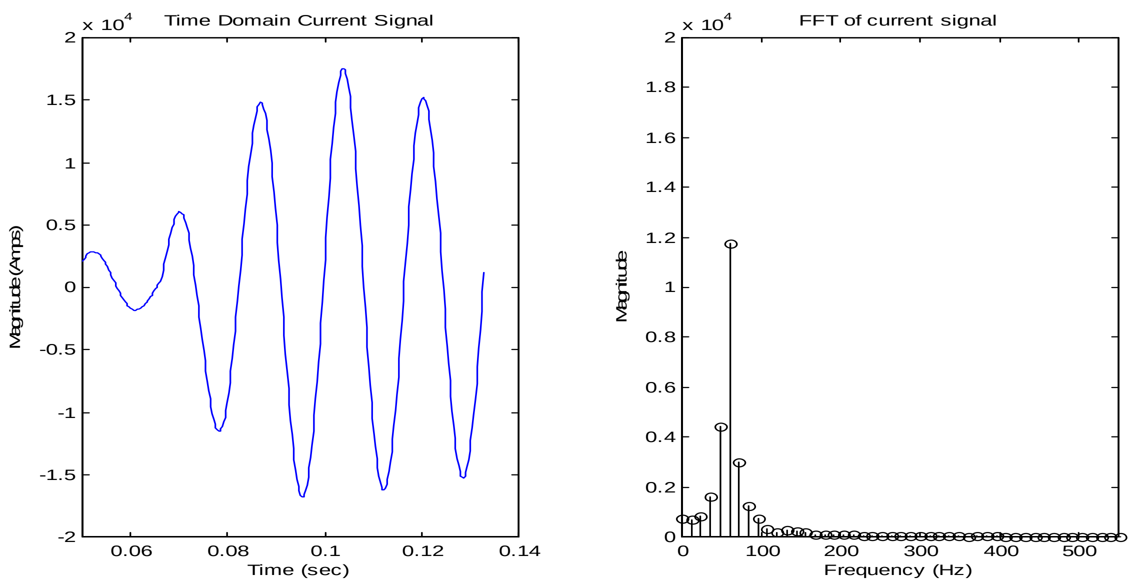


Figure D.5 – Evolving Fault with no MOV Operation

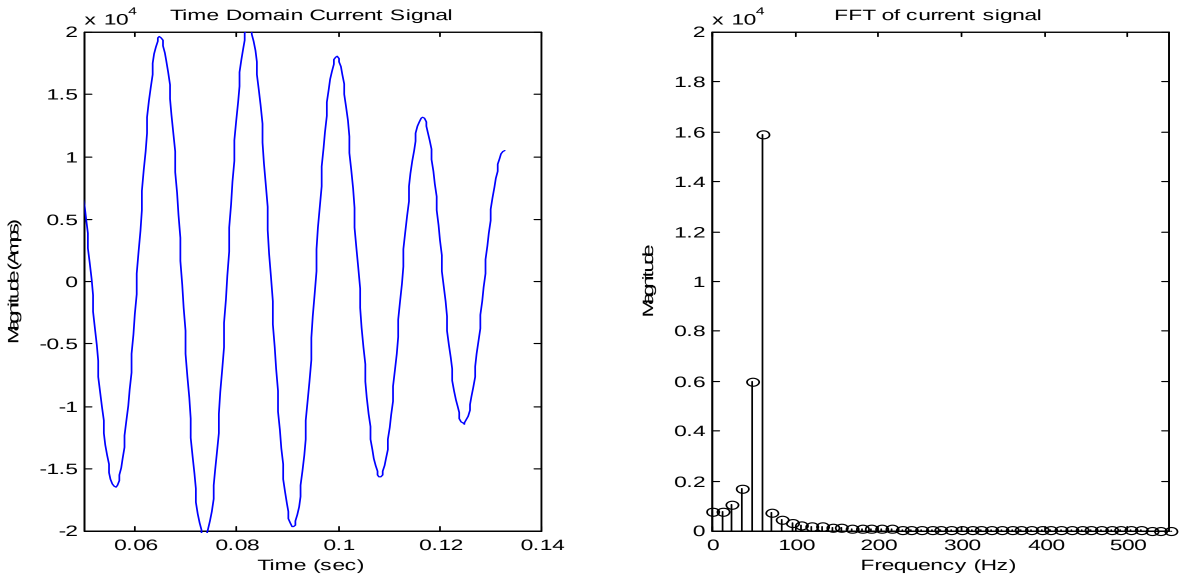


Figure D.6 – Evolving Fault with no MOV Operation

MATLAB Code for MOV Detection Algorithm

```
%%%% Test of Algorithm to Determine MOV Operation %%%%
clear
% Input Fault Type
% Types are  1=ag 2=bg 3=cg 4=ab 5=bc 6=ca 7=abg
%             8=bcg 9=cag 10=abc

FT=2;

% Input Data

x=wk1read('c:\movdetect\evol000n');
ee=512;
x=x(193:ee,:);

%% Note that the first cycle of post fault data was ignored to avoid the possibility
%% of erroneous results due to the "step change" caused by the fault inception.

nu=length(x);
time=(x(5,1)-x(4,1));

Ia=x(:,3);             Va=x(:,2);
Ib=x(:,5);             Vb=x(:,4);
Ic=x(:,7);             Vc=x(:,6);

%% Choose a current signal for a phase which was involved in the fault

if FT==1 | FT==4 | FT==6 | FT==7 | FT==9 | FT==10
       testI=Ia;
end

if FT==2 | FT==5 | FT==8
```

```
        testI=Ib;
 end

if FT==3
       testI=Ic;
end

%% Print the current waveform

subplot(1,2,1)
plot(x(:,1),testI)
title('Time Domain Current Signal')
xlabel('Time (sec)')
ylabel('Magnitude (Amps)')
%axis([0.05 0.14 -5500 5500 ])
axis([0.05 0.14 -20000 20000 ])



%% Comput the FFT of the current signal

testp=fft(testI);
testp=abs(testp);
num=length(testp);
f=(1/(time)*((0:num-1)/num));
subplot(1,2,2)
stem(f,(testp*2/nu),'k');
title('FFT of current signal')
xlabel('Frequency (Hz)')
ylabel('Magnitude')
%axis([0 550 0 4000])
axis([0 550 0 20000])

%% Determine the percentage of 3rd, 5th, 7th and 9th harmonics present in the signal

ratio1=testp(16)/testp(6)
ratio2=testp(26)/testp(6)
ratio3=testp(36)/testp(6)
ratio4=testp(46)/testp(6)

if ratio1>=.05 & ratio2>=.05 & ratio3>=.05 & ratio4>=.05
'MOV has operated!!  Capacitor was part of fault circuit...Results of this algorithm may be
questionable!!'
end

Average=(ratio1+ratio2+ratio3+ratio4)/4

End
```

Clint T. Summers

Clint was born in 1974 to Charles and Valerie Summers of Baltimore, Maryland. He graduated from Towson Senior High School in 1992. Clint began his engineering studies that same year in Blacksburg, Virginia at Virginia Polytechnic Institute and State University where he completed his BSEE in 1996. At that time he took a GTA / GRA position working and studying under advisor Arun G. Phadke. He completed his MSEE coursework in the power area in 1998 and began work with the Morrison Knudsen Corporation in their Columbia, Maryland offices. Clint is an electrical engineer with Morrison Knudsen and works with the State Department of the US government on projects involving US missions abroad. Clint completed and defended his thesis in September of 1999 and returned to work with the Morrison Knudsen Corporation.